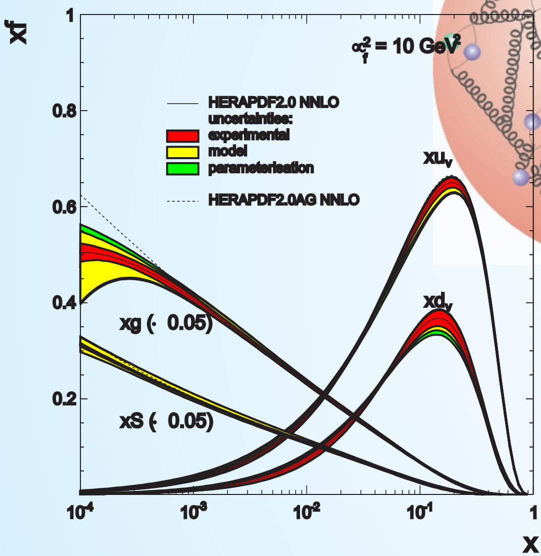
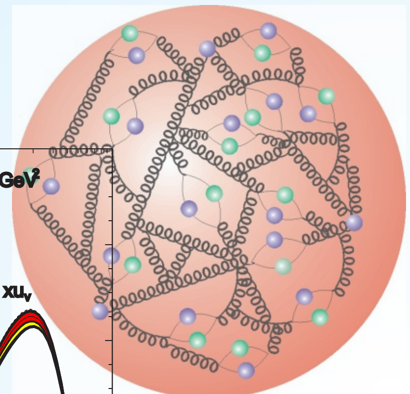
Remember HERA





and what she can tell you ....

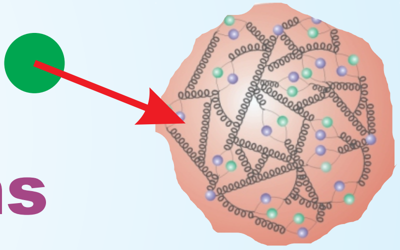
I.Abt, MPI München

Regensburg, 19.3.2018

Content

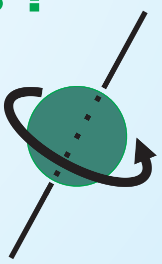
- **HERA**
  - **Goals and Experiments**
  - **Some tales and decisions**
  - **Some results**

- **Deep Inelastic Scattering**
  - **Parton Distribution Functions**

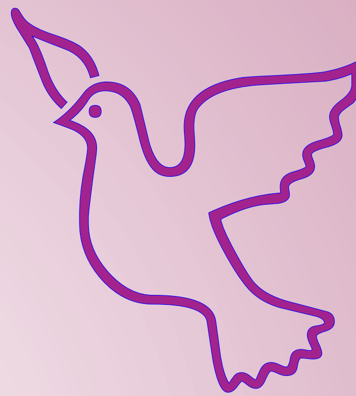


- **Proton Structure**
  - **Photon Structure**

- **Data Taking and Publishing**
- **Some Final Words**



DISCLAIMER

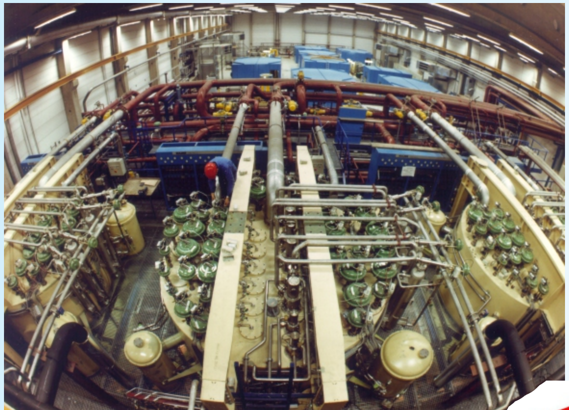


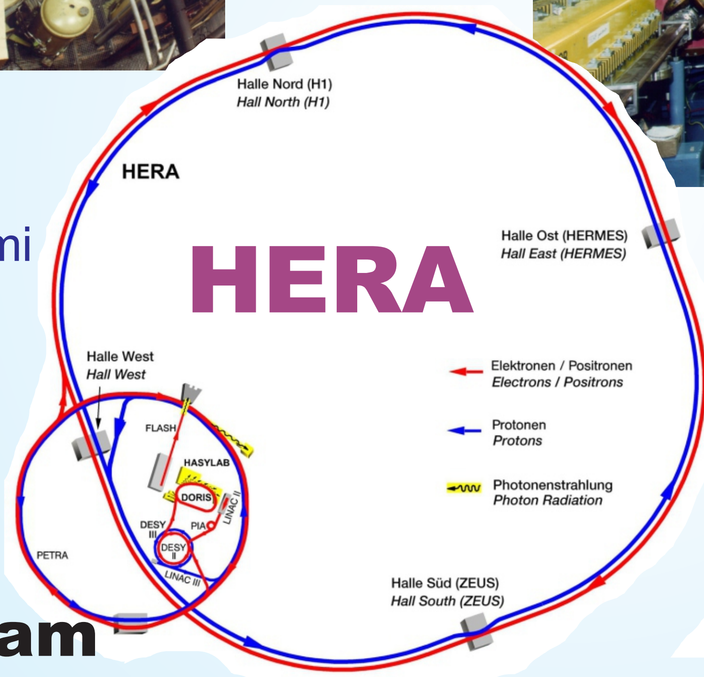
I will not try to be complete on any subject.
I have selected what I saw fit to make my point.
Any opinion is mine and only mine and is in no way supported by either ZEUS or H1 or probably anybody else.

Nevertheless I am proud to represent ZEUS and H1 as far as their results are concerned.

And I am sorry, if I should disturb you doing your Email or reading your favorite newspaper.

HERA





24.5.1993

Zeus DIS Lumi

HERA I

– 2000

2003 –

HERA II

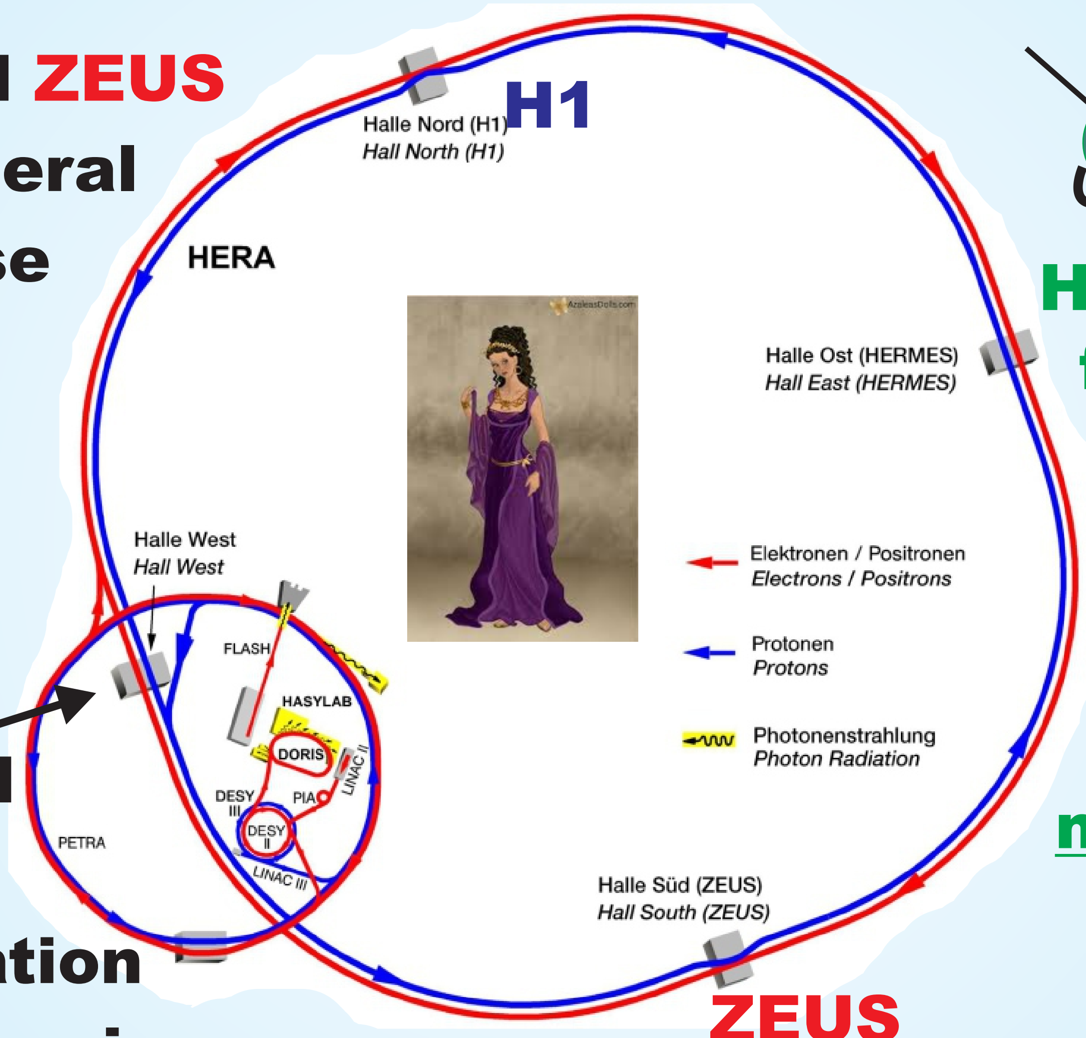
last beam

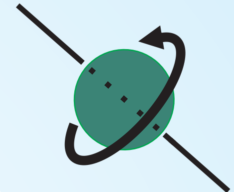
30.6.2007

HERA

H1 and ZEUS

ep general purpose





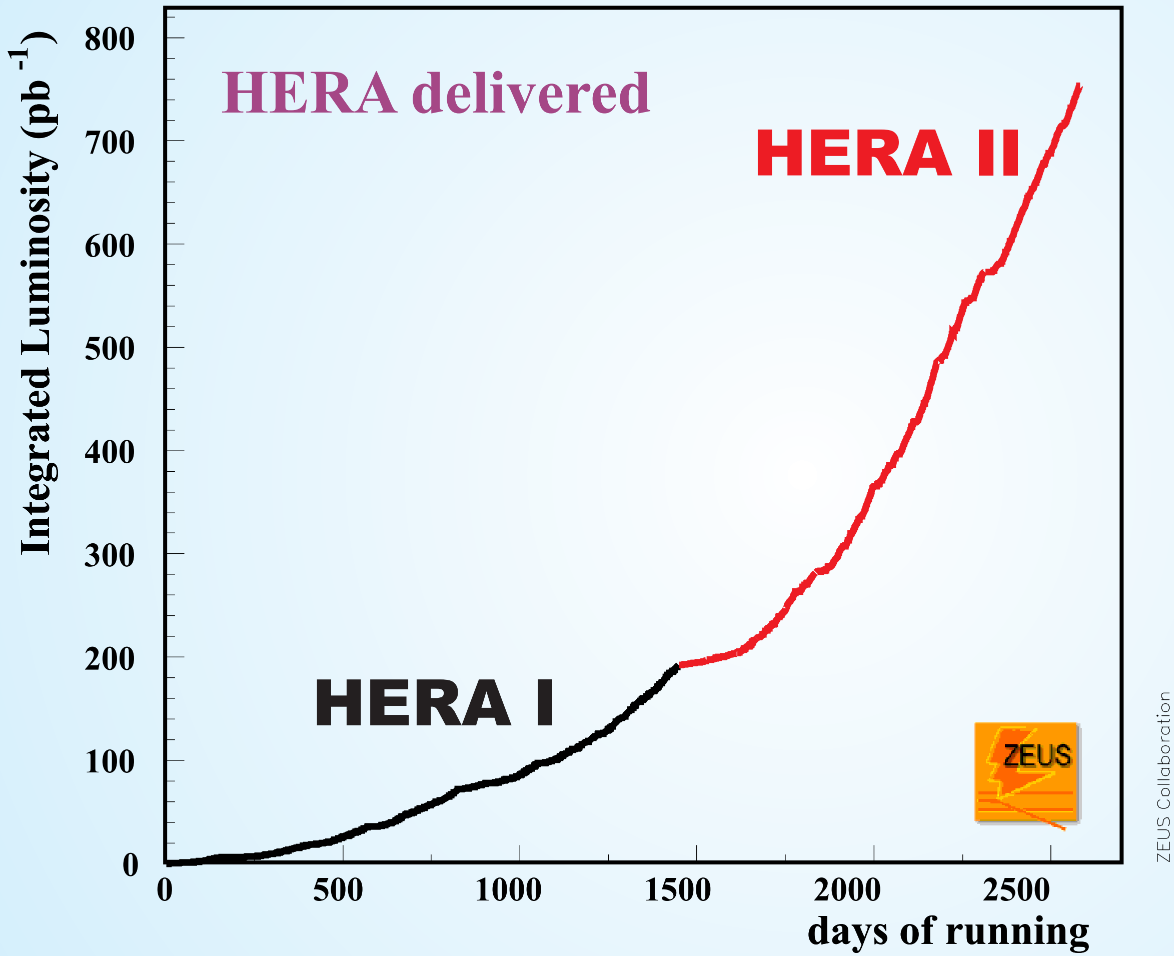
HERMES fixed target spin physics <u>**not for me to cover**</u>

<u>**sad story**</u>**:**

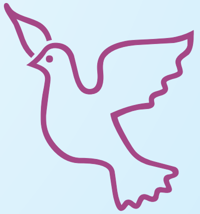
HERA-B

pN fixed target CP violation and b physics

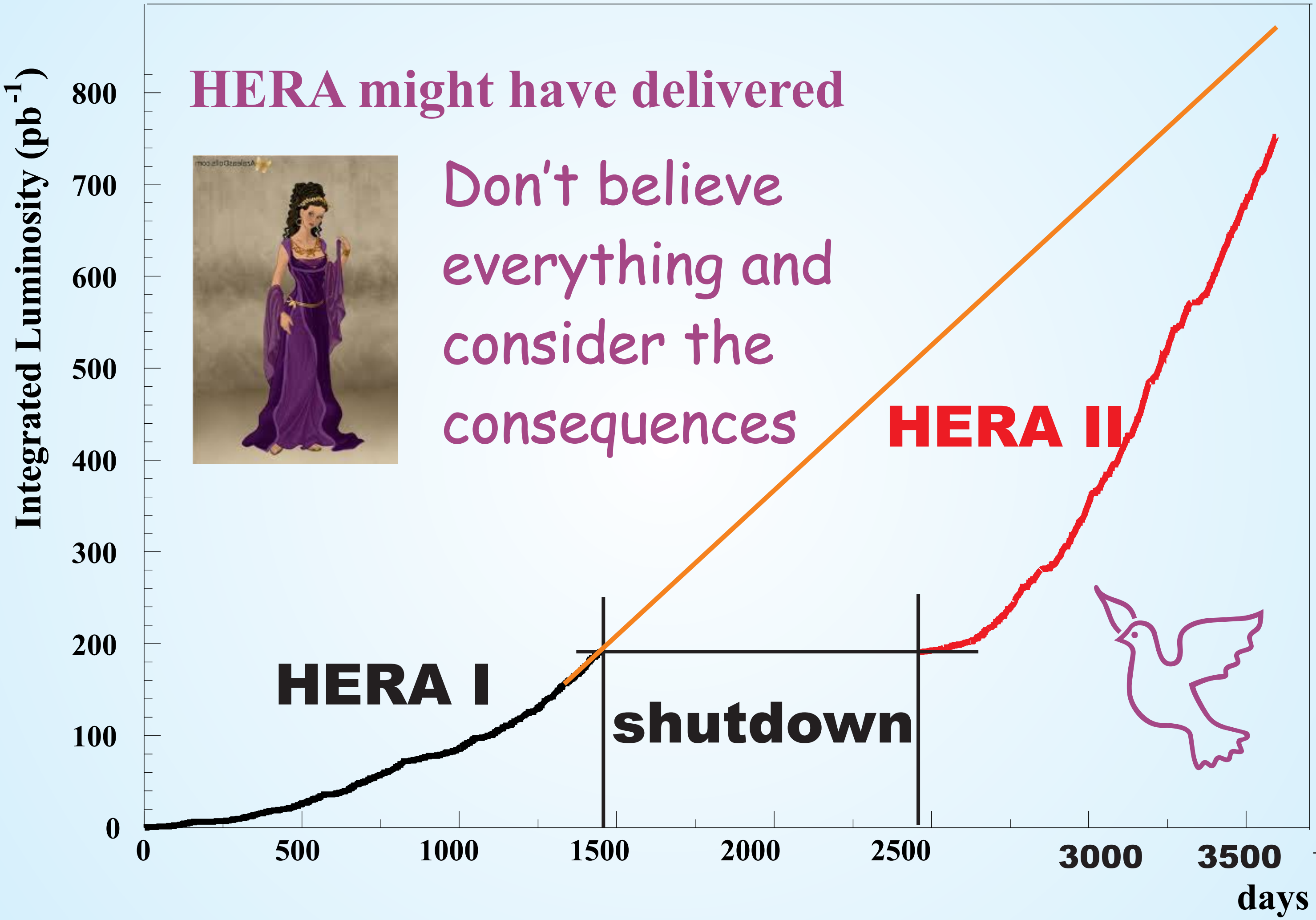
HERA-Luminosity



The upgrade was worth it.

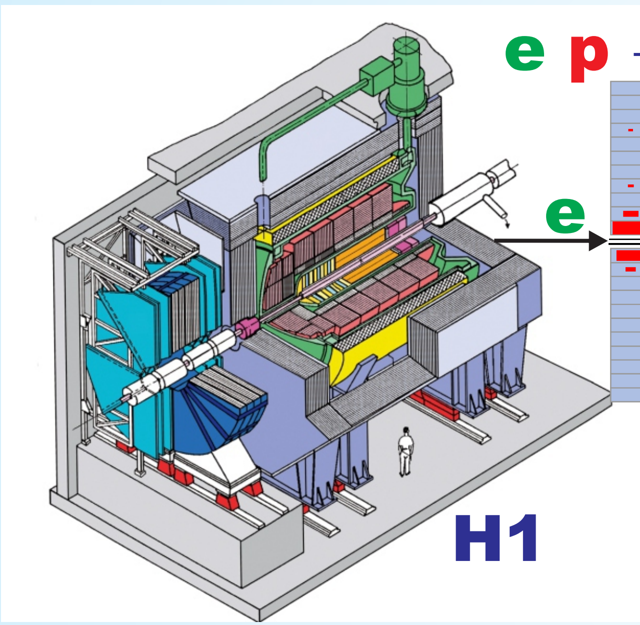


HERA-Luminosity

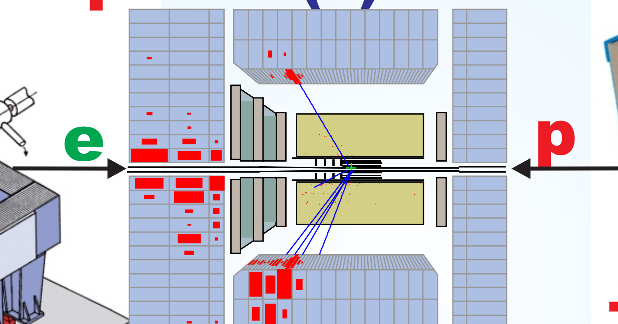


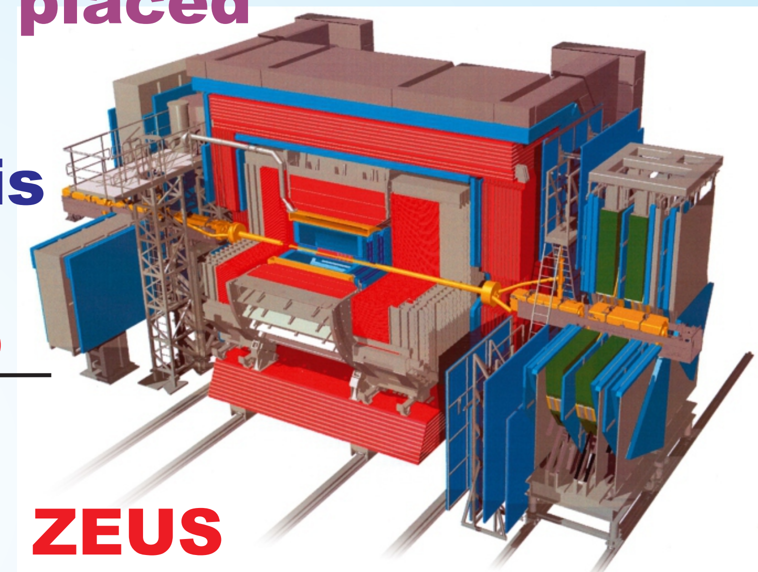
Detectors

During HERA II magnets were placed inside ZEUS and H1.



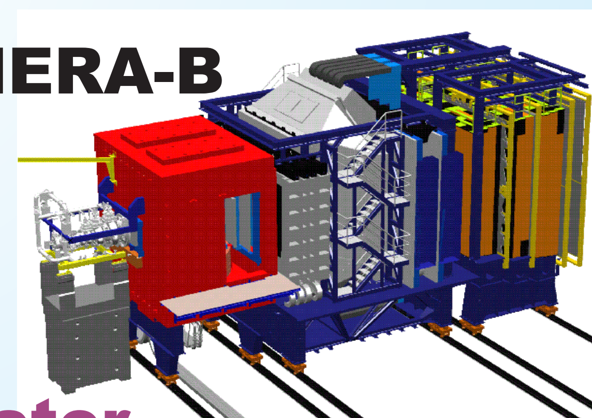
e p → e (ν) debris





HERA-B

p → N

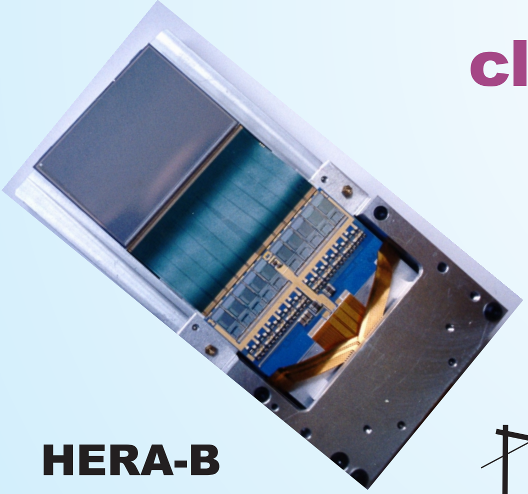


Detector architecture depends on event configuration, but everybody wants a vertex detector

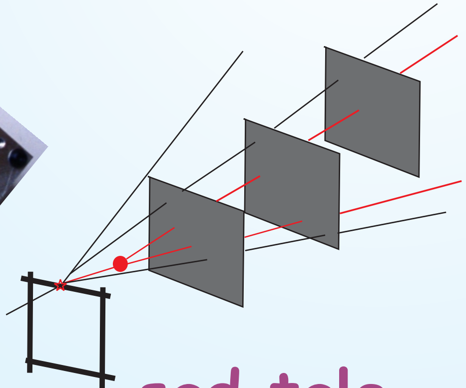
Vertex Detectors

They are beautiful toys.
But check what you really need
and consider what they do to the
stuff behind it.

Don't get stuck on
classical geometries.



HERA-B
vertex tracker



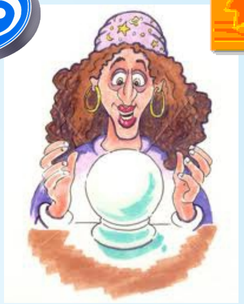
sad tale

Sometimes the
silicon vertex detector
is the only thing
that works.

Goals

HERA was a child of the eighties:

- **unification was around the corner**
  ==> look for leptoquarks
- **discoveries were expected**
  ==> look for signs of Z', extra Ws
  ==> look for signs of SUSY



Everybody was wrong

Be flexible !

HERA has not found anything BSM.

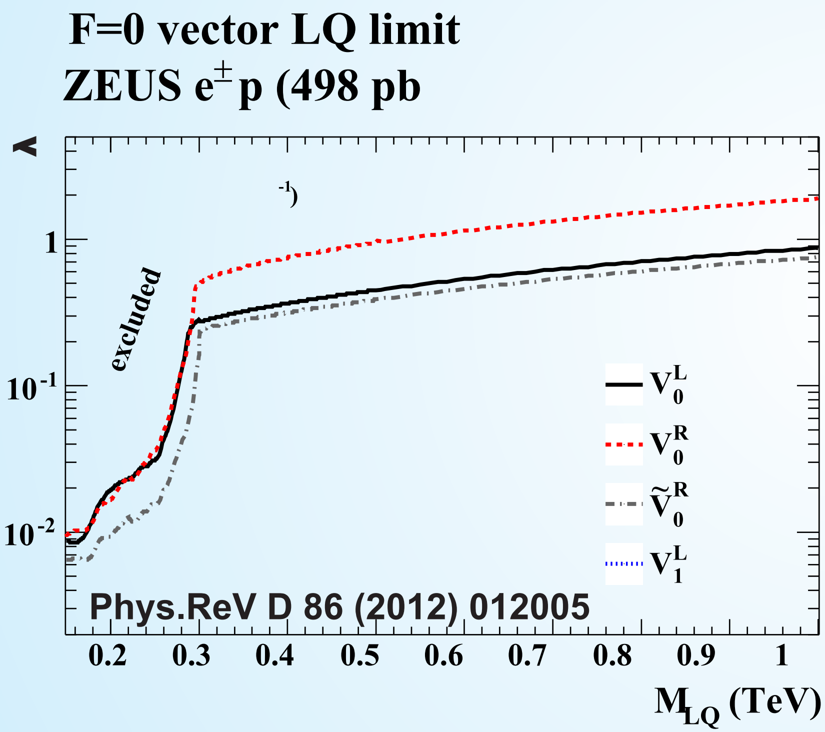
Sometimes it's good to have two experiments: believe it when they find the same new thing!

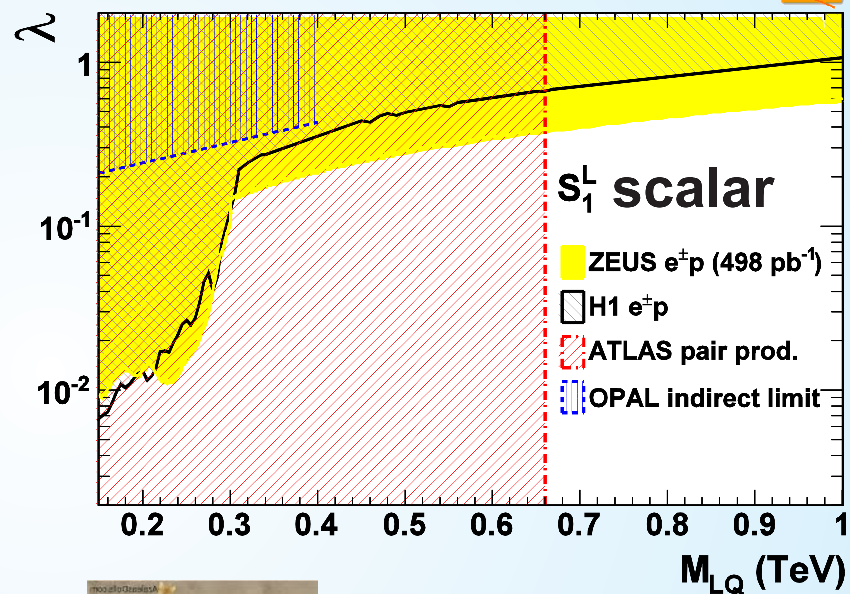
==> HERA became a QCD machine with DIS, heavy quarks etc.

But never forgot the old goals.

Leptoquarks

Unfortunately, there are endless varieties of what can be excluded:

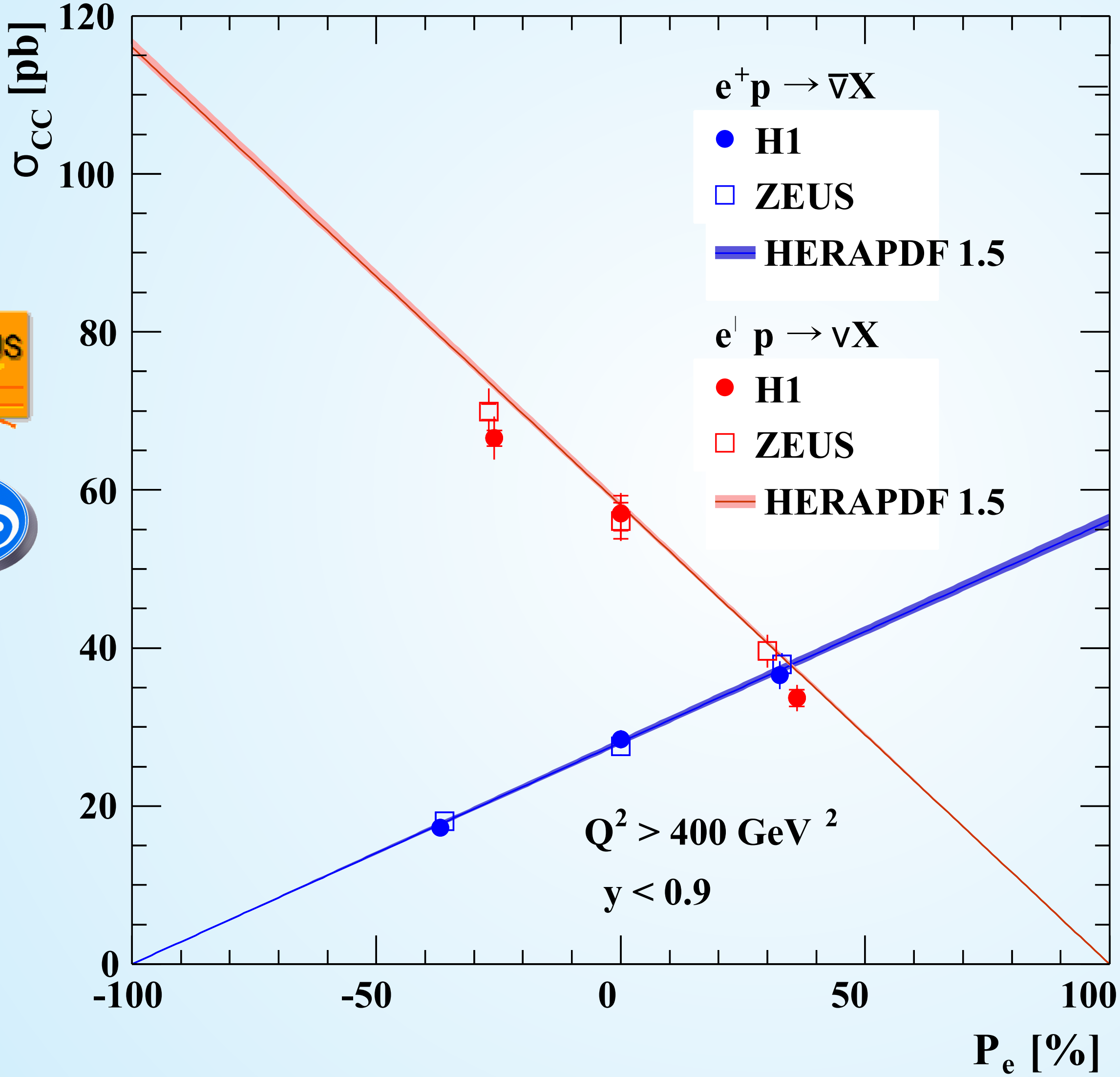




HERA results are valid.

Models are very different at LHC and results should not be compared.

V-A and Parity violation

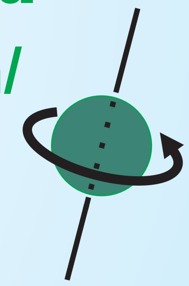


HERA

Charged Current

e^+p / e^-p scattering

Polarised electron/ positron beams



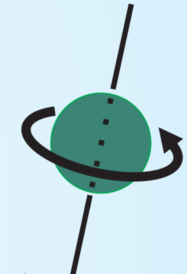
Polarisation, well.....

Beam Polarisation

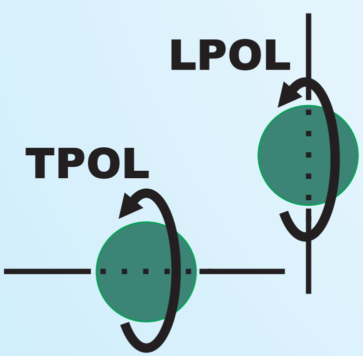
Polarisation is important so they say.

However, for ep, it was not used much.

EW Analyses did not become the main focus.



Polarisation needs to be measured, and that is easier said than done.



Never build more than one polarimeter, it ruins the uncertainties.

$\%^2 + \%^2$

The Proton

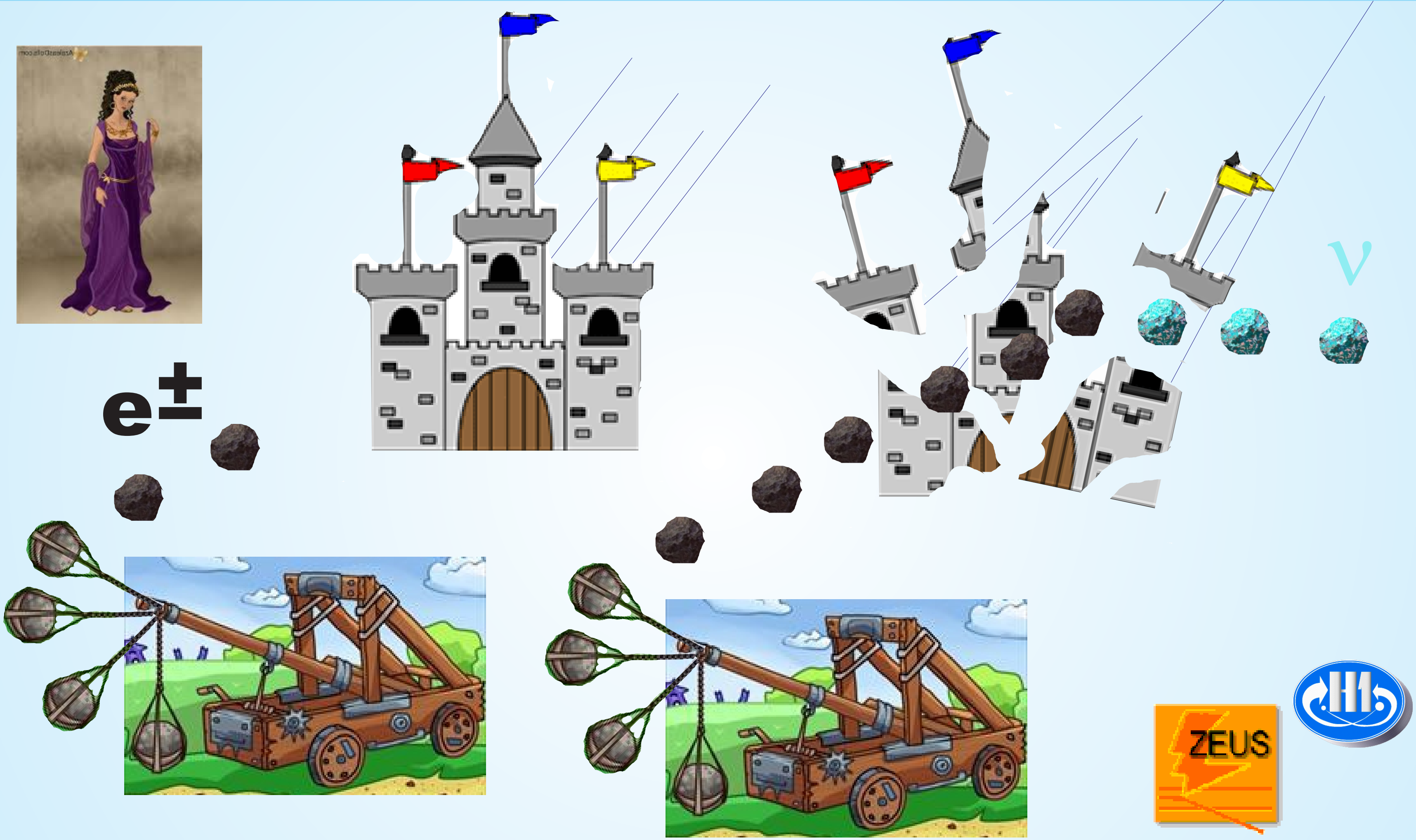
What do I really know about the proton:

- mass = 1GeV = 1.67 10 $^{-27}$ kg
- 3 valence quarks
- charge = +1
- spin = 1/2 → Spin
- radius ≈ 1 fm; shape?
- afflicted by QCD
- lifetime » age of the universe

I have no real explanation for any of this !

Nevertheless I am famous for studying it.

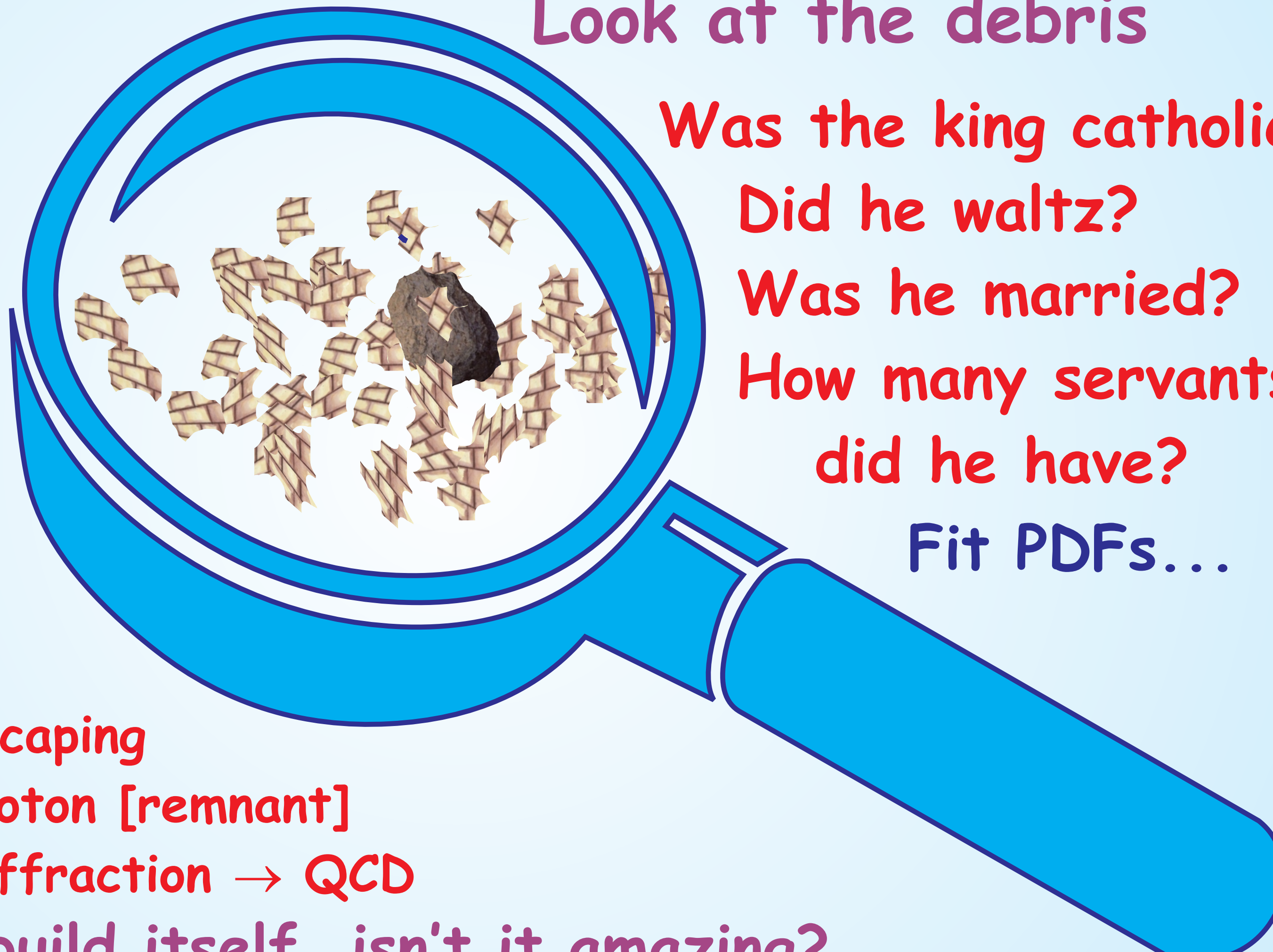
Deep Inelastic Scattering



I shot with electrons and destroyed whenever possible.

Deep Inelastic Scattering

Look at the debris



Was the king catholic?

Did he waltz?

Was he married?

How many servants did he have?

Fit PDFs...

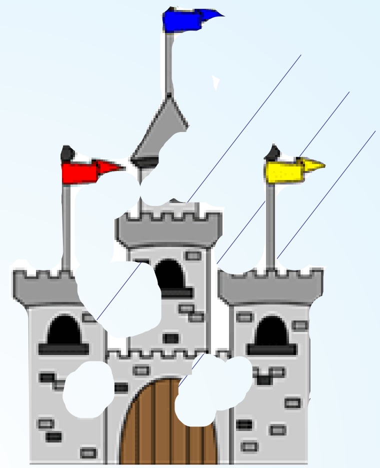
Escaping proton [remnant]

Diffraction → QCD

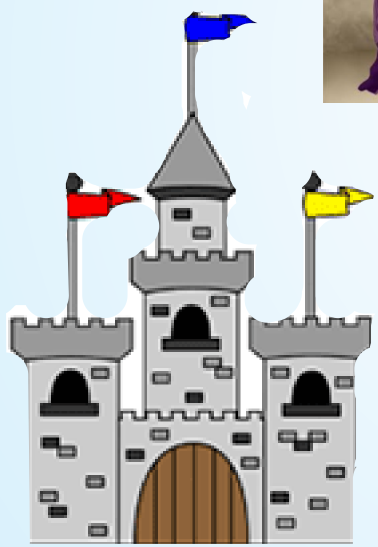
This can rebuild itself, isn't it amazing?

Diffraction

Both lost their forward instrumentation for HERA II.



Interaction regions are important !



≈20%

Unfortunately, did not manage to agree on normalisation, but for a small part of the phase space.

Kinematics

Virtuality $Q^2 = -(k - k')^2$

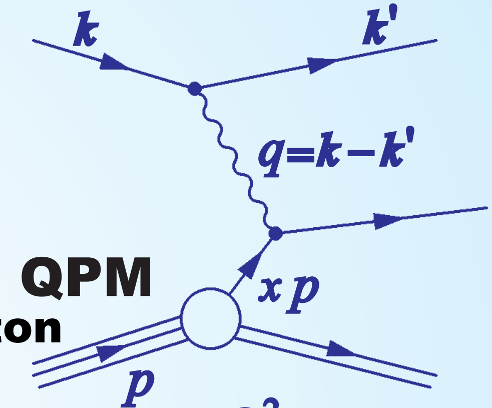
Spatial resolution of probe

$\lambda \sim 1/\sqrt{Q^2}$

Bjorken scaling variable:

$x = Q^2 / 2pq$

Momentum fraction of struck parton



Inelasticity: $y = pk / pq$

$Q^2 = xys$

Energy transfer to proton (in p rest frame)

HERA was at her best for NC, but CC is also important.

Reconstruction

$$y_e = 1 - \frac{E'_e(1 - \cos\theta_e)}{2E_e} \qquad Q^2_e = \frac{{E'_e}^2 \sin^2\theta_e}{1 - y_e} \qquad x_e = \frac{Q^2_e}{4E_pE_ey_e}$$

Factorisation

Decompose cross section:

$$\sigma(ep \to e + H + X) = \sum_{j,j'=q,\bar{q},g} f_{j/p}(x,Q) \otimes \hat{\sigma}_{jj'}(x,Q,z) \otimes F_{H/j'}(z,Q)$$

parton distribution functions — PDF

partonic cross section

hadronisation

NC $V^* = \gamma^*, Z^*$

Born $V^* q \to q$

boson-gluon-fusion $V^* g \to q\bar{q}$

QCD-Compton-scattering $V^* q \to qg$

CC W^*

$V^* q \to q'$

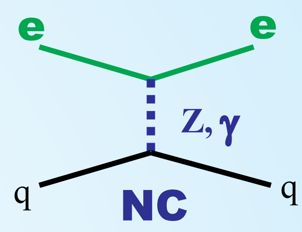
lowest-order QCD

Many attempts, but violation of factorisation could not be shown.

Structure Functions

$e^{\pm}p$

tree level $\quad \sigma^{\pm}_{r,\mathrm{NC}} = \dfrac{\mathrm{d}^2\sigma^{e^{\pm}p}_{\mathrm{NC}}}{\mathrm{d}x\mathrm{d}Q^2} \cdot \dfrac{Q^4 x}{2\pi\alpha^2 Y_+} = \tilde{F}_2 \mp \dfrac{Y_-}{Y_+} x\tilde{F}_3 - \dfrac{y^2}{Y_+}\tilde{F}_L$



$$\tilde{F}_2 = F_2 - \kappa_Z v_e \cdot F_2^{\gamma Z} + \kappa_Z^2 (v_e^2 + a_e^2) \cdot F_2^Z$$

$$\tilde{F}_L = F_L - \kappa_Z v_e \cdot F_L^{\gamma Z} + \kappa_Z^2 (v_e^2 + a_e^2) \cdot F_L^Z$$

$$x\tilde{F}_3 = \kappa_Z a_e \cdot xF_3^{\gamma Z} - \kappa_Z^2 \cdot 2 v_e a_e \cdot xF_3^Z$$

$Y_{\pm} = 1 \pm (1-y)^2$

v_e vector
a_e axial-vector
eZ weak couplings

$$\kappa_Z(Q^2) = Q^2/[(Q^2 + M_Z^2)(4\sin^2\theta_W \cos^2\theta_W)] \qquad (2)$$

QPM $\quad \tilde{F}_L = 0$

$$(F_2, F_2^{\gamma Z}, F_2^Z) = [(e_u^2, 2e_u v_u, v_u^2 + a_u^2)(xU + x\bar{U}) + (e_d^2, 2e_d v_d, v_d^2 + a_d^2)(xD + x\bar{D})]$$

$$(xF_3^{\gamma Z}, xF_3^Z) = 2[(e_u a_u, v_u a_u)(xU - x\bar{U}) + (e_d a_d, v_d a_d)(xD - x\bar{D})]$$

$$xU = xu + xc \qquad x\bar{U} = x\bar{u} + x\bar{c} \qquad xD = xd + xs \qquad x\bar{D} = x\bar{d} + x\bar{s}$$

sea quarks =anti-quarks

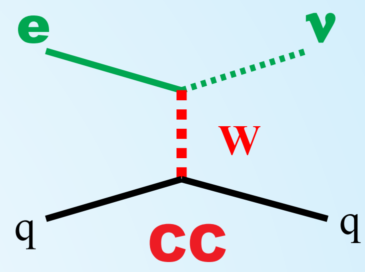
valence quark distributions $\quad xu_v = xU - x\bar{U} \qquad xd_v = xD - x\bar{D}$

Structure Functions

$e^{\pm}p$

tree level

$$\sigma^{\pm}_{r,CC} = \frac{Y_+}{2} W_2^{\pm} \mp \frac{Y_-}{2} x W_3^{\pm} - \frac{y^2}{2} W_L^{\pm}$$



CC is unfortunately a bit more difficult.

QPM $W_L^{\pm} = 0$

$W_2^+ = x\overline{U} + xD$ $\quad xW_3^+ = xD - x\overline{U}$ $\quad W_2^- = xU + x\overline{D}$ $\quad xW_3^- = xU - x$

$$\sigma^{+}_{r,CC} = x\overline{U} + (1-y)^2 xD \qquad \sigma^{-}_{r,CC} = xU + (1-y)^2 x\overline{D}$$

NC and CC yield valence and sea quark distribution.

QCD analysis [DGLAP] yields gluon distribution.

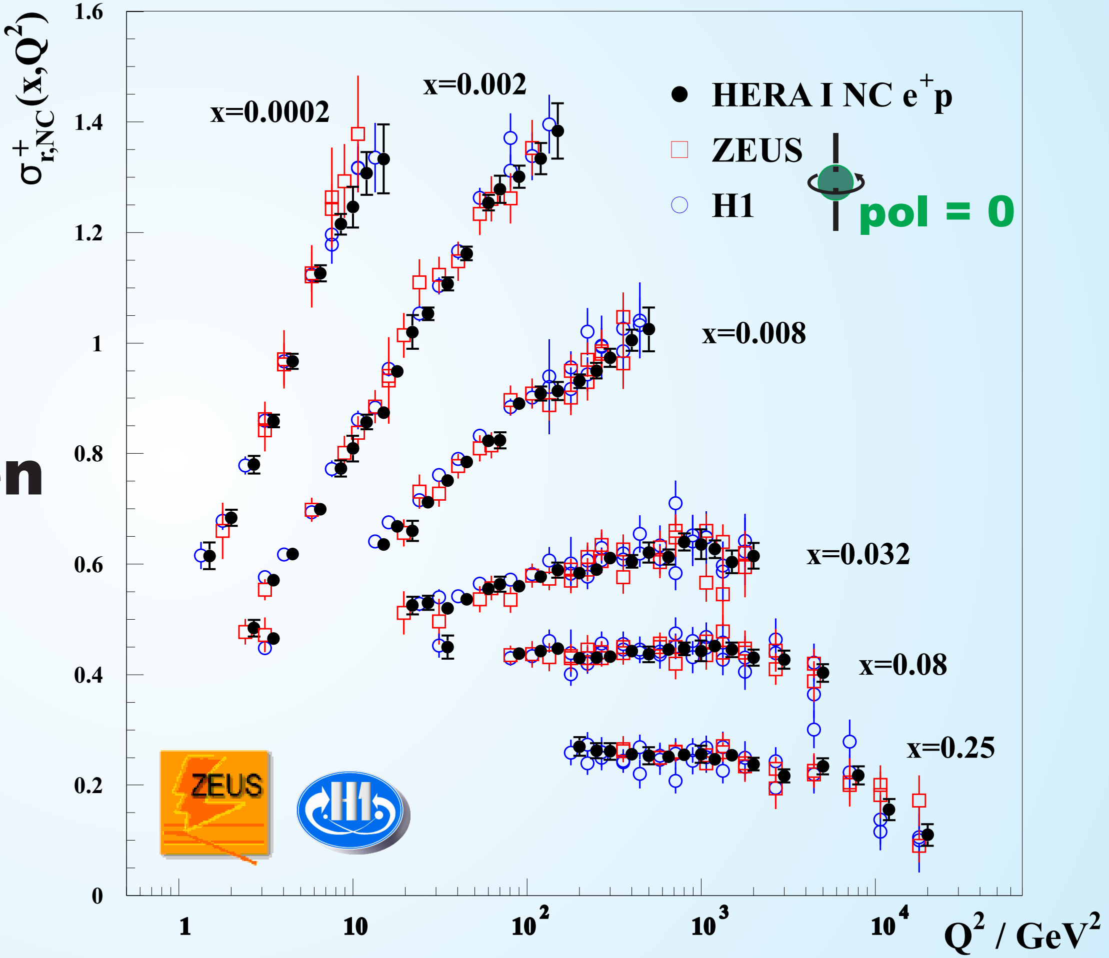
HERA I cross sections

Combining Data is not easy !

2010:

H1 and ZEUS publish combined results on data taken 1993 to 2000.

10 years of fighting to understand detectors, methods and systematics.



Eur. Phys. J C 75 (2015) 580

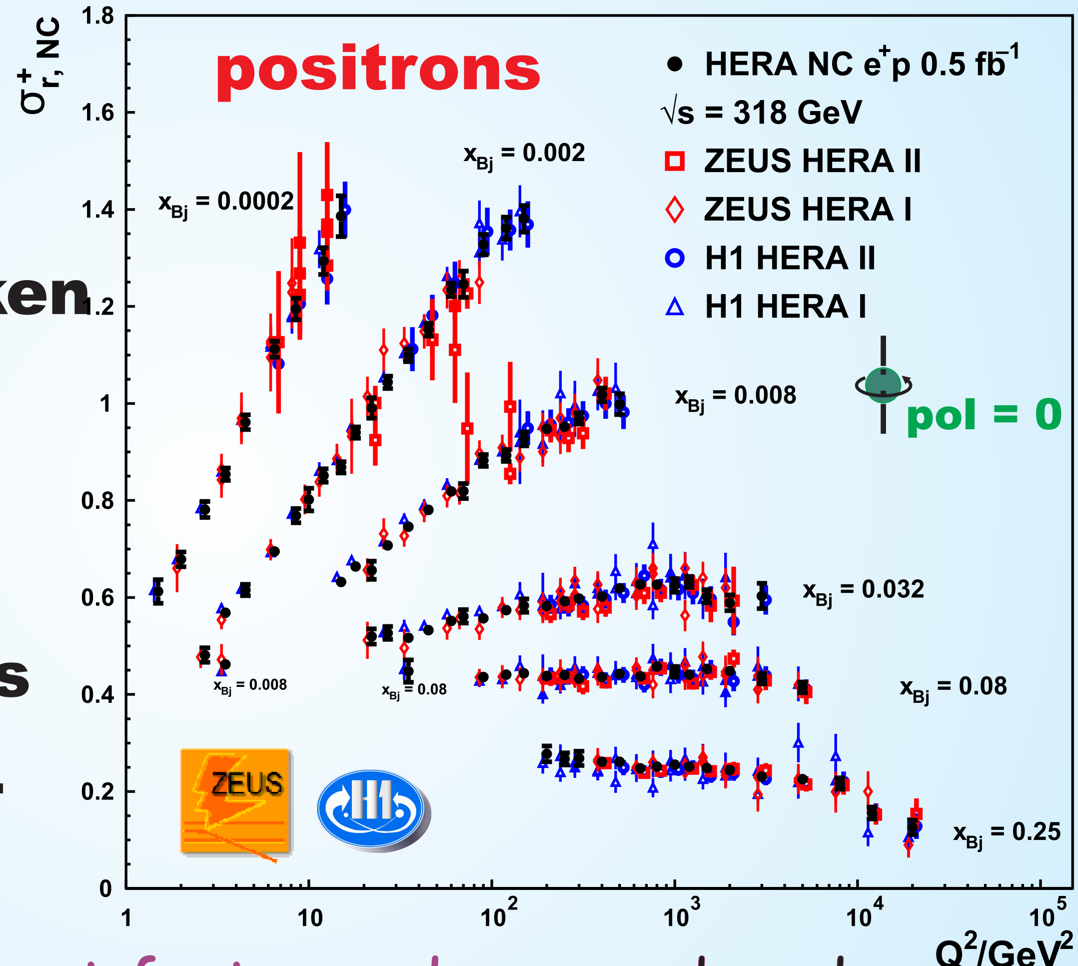
HERA cross sections

2015:

H1 and ZEUS publish combined results on data taken 1993 to 2007.

8 years of fighting to understand detectors, methods

and syste-matics

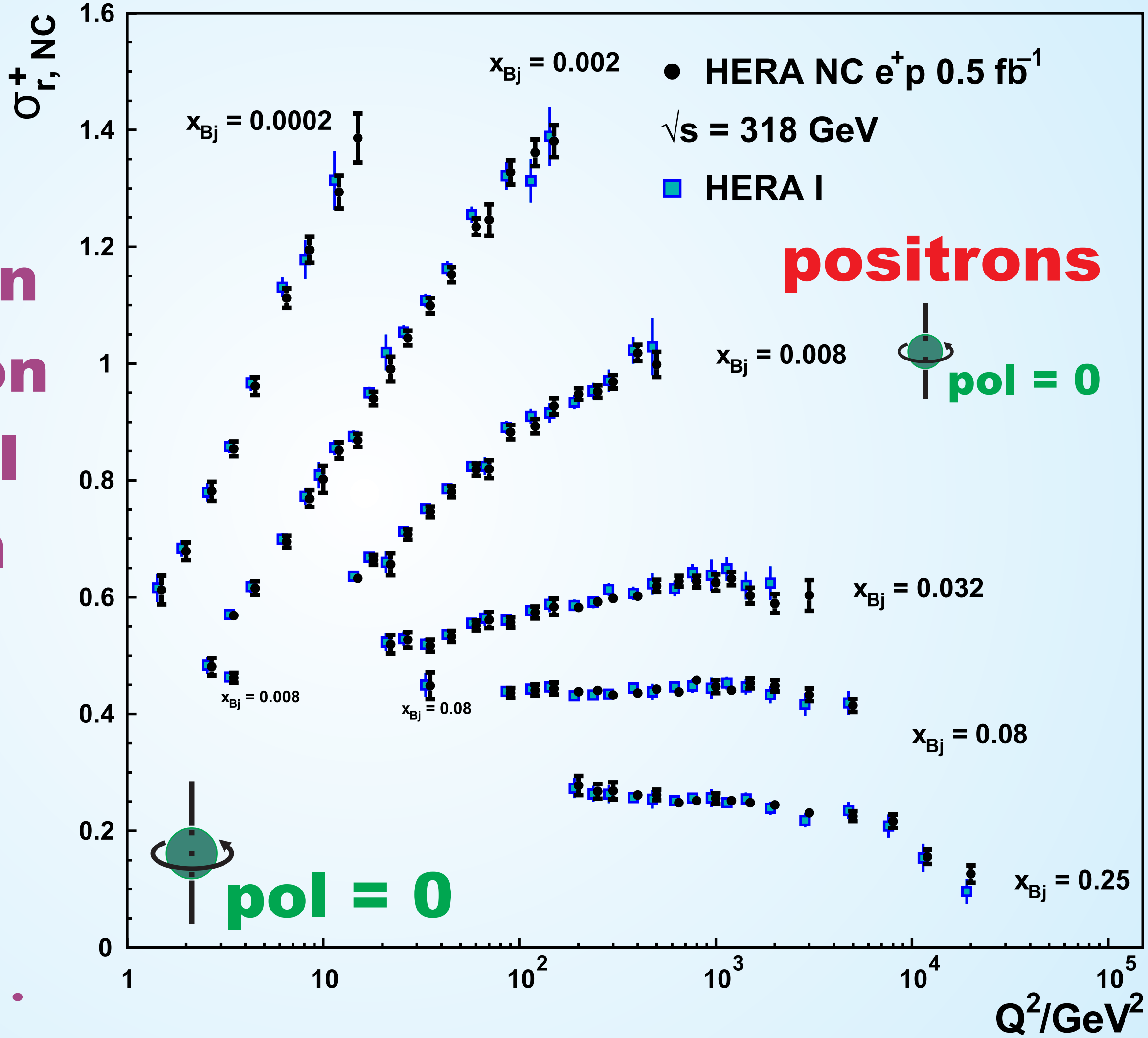


My children got faster and σ → reduced σ

HERA cross sections

My children even agree on HERA I and II and between ZEUS and H1.

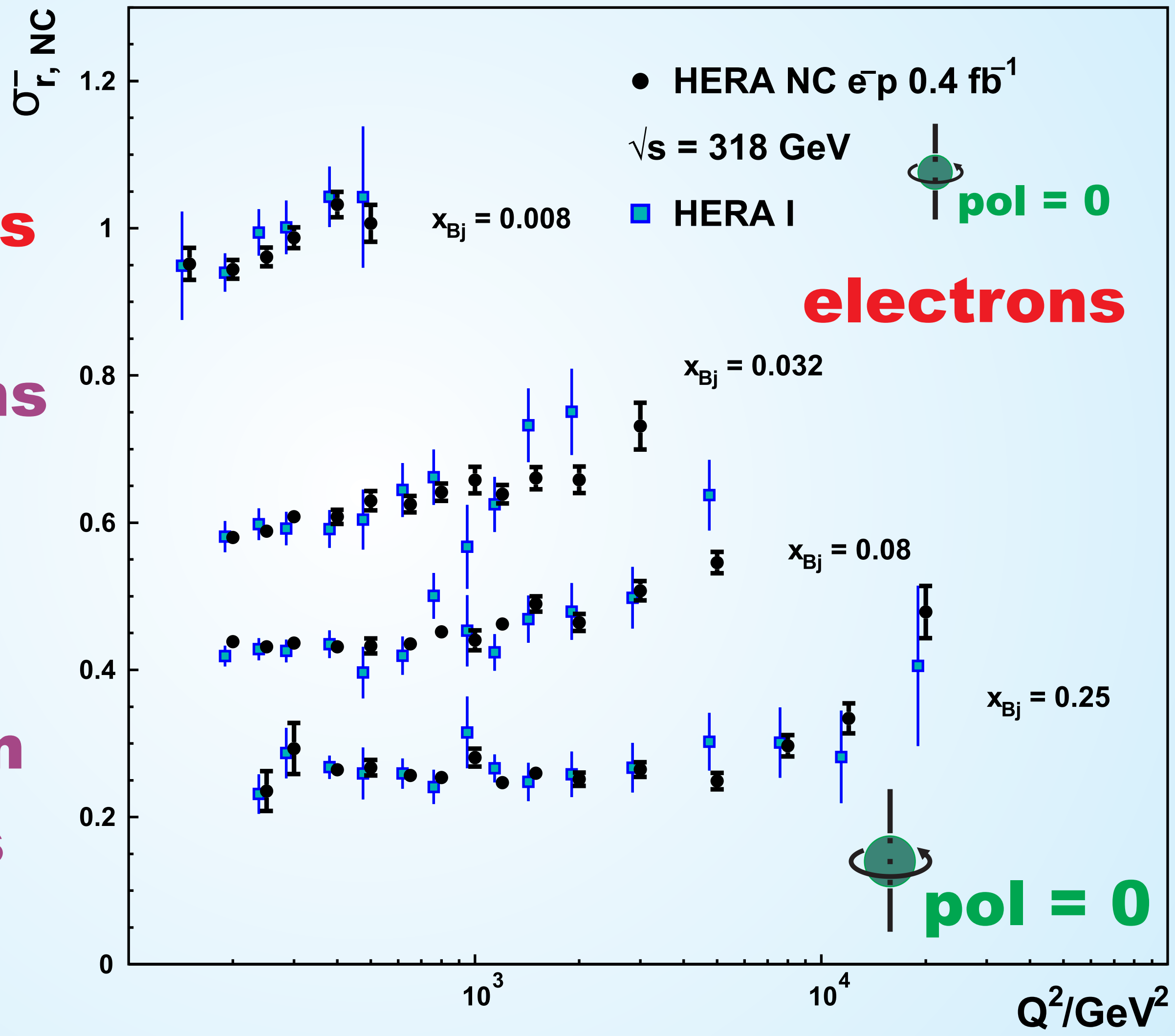
The latter is a bit of a miracle....



HERA cross sections

Improvement is larger for electron beams

Electrons can be tricky; they can form space charges and what not.



HERA cross sections

41 data sets taken over 14 years

162 correlated systematic uncertainties

correlations between correlated uncertainties

different collaborations

different x, Q_2 grids

2927 $\rightarrow$ 1307 points

χ^2/dof = 1.04

pol = 0

Eur. Phys. J C 75 (2015) 580

You should agree on
grids, corrections and how you publish.
Best, publish event numbers.

HERAPDF 2.0

All 1145 cross sections with $Q^2 \geq 3.5$ GeV^2 are input to a QCD analysis within the framework of DGLAP perturbative QCD.

HERAPDF2.0 NNLO NLO LO

high Q^2	$Q^2 > 10$ GeV^2
AG	alternative gluon
FF 3A/B	fixed flavour
Jets	includes charm and jet data $\rightarrow \alpha_s$

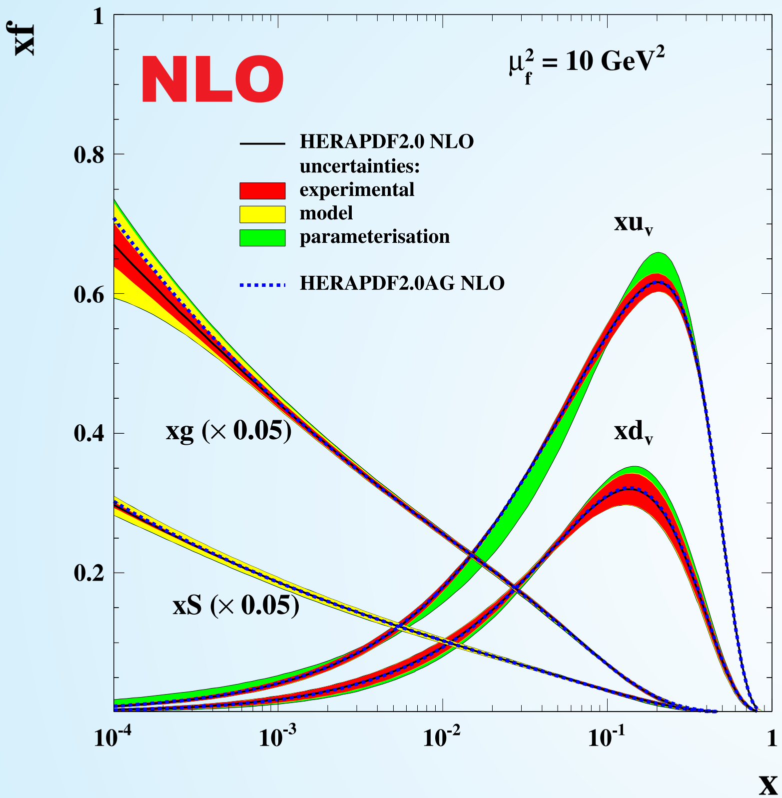
Hera likes a good fit!

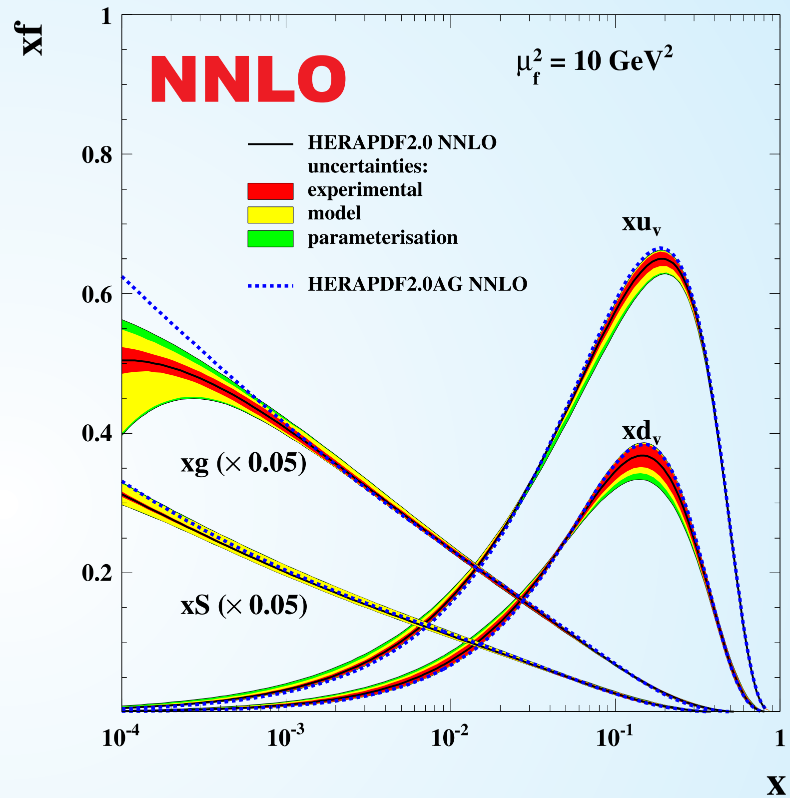
HERAFitter → xfitter

and independent code

Overview in Eur. Phys. J C75 (2015) 580 App.1 and 2.

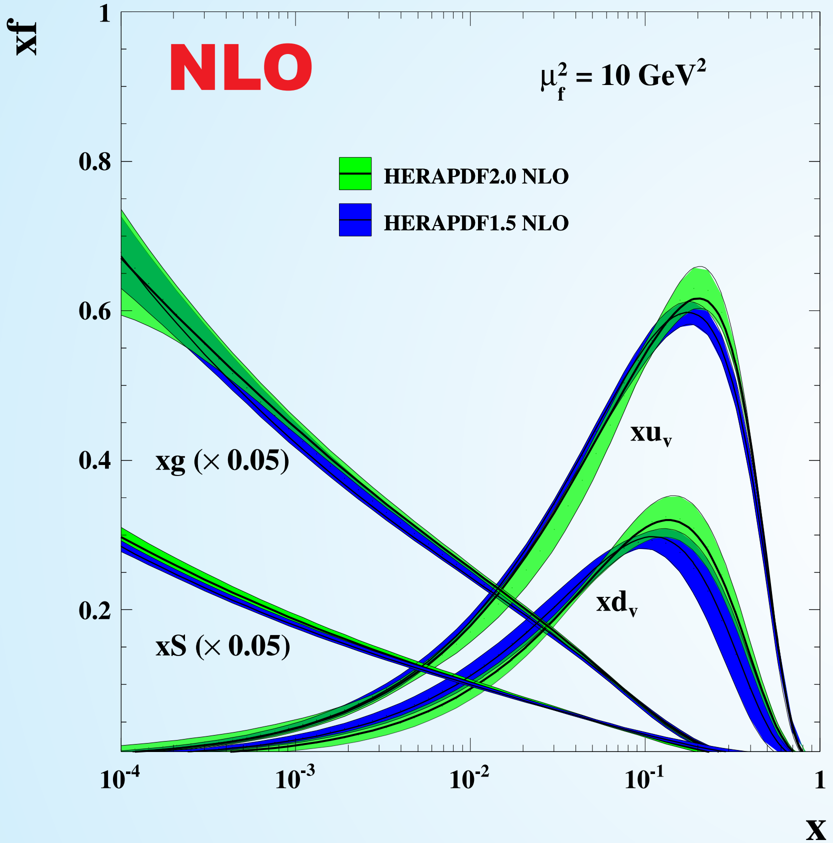
HERAPDF 2.0

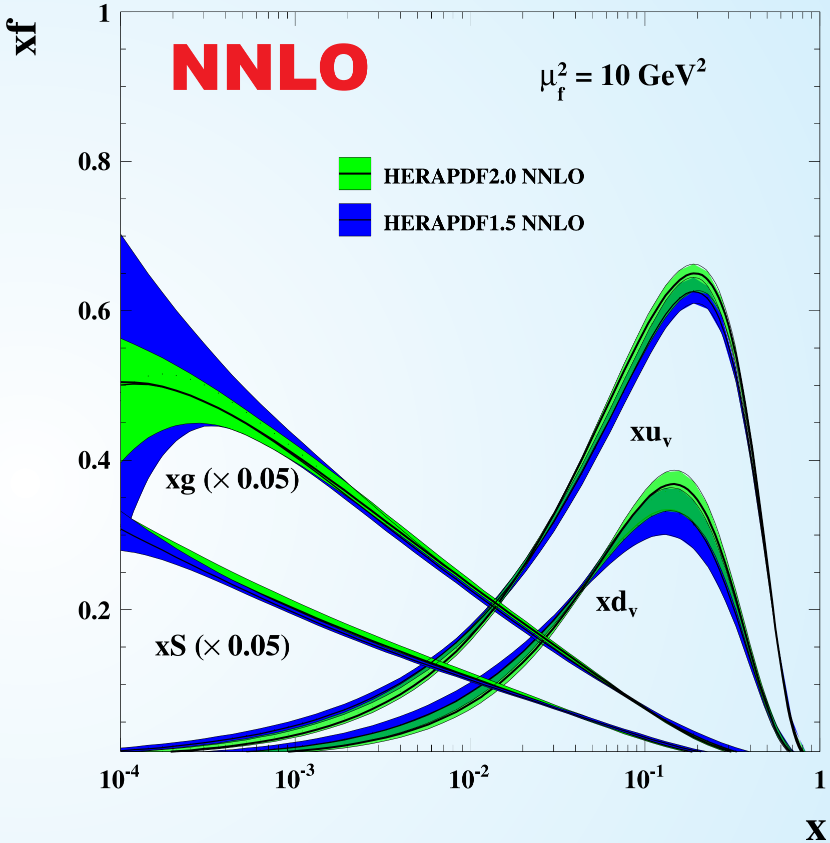




HERAPDF 2.0 NLO and 2.0 NNLO are the recommended PDFs for general useage.

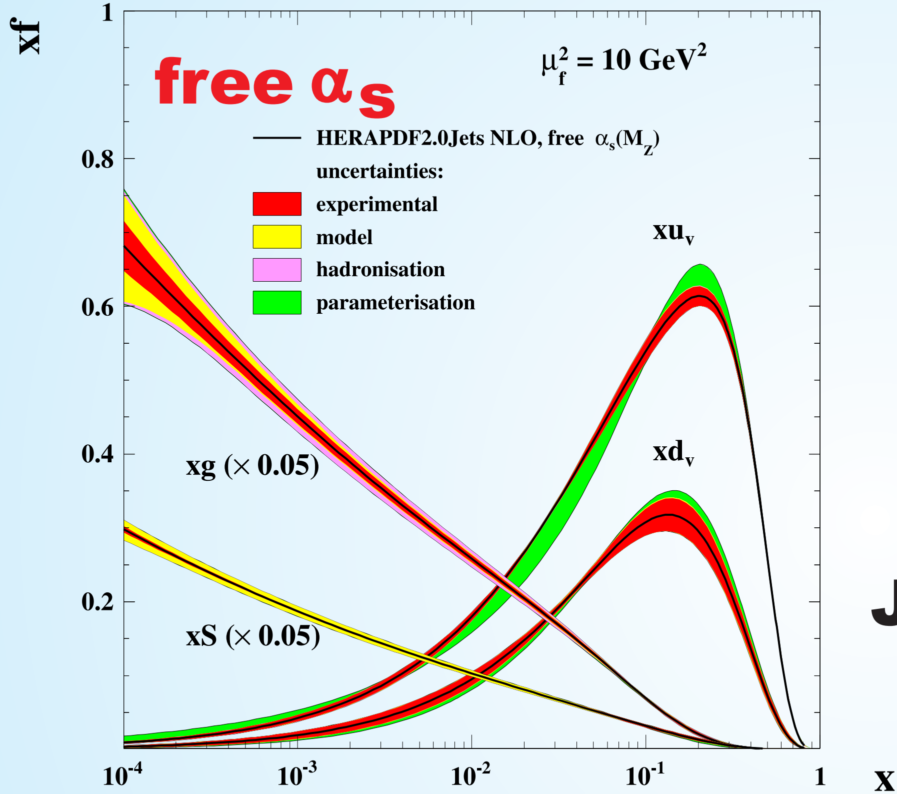
HERAPDF 2.0 and 1.5

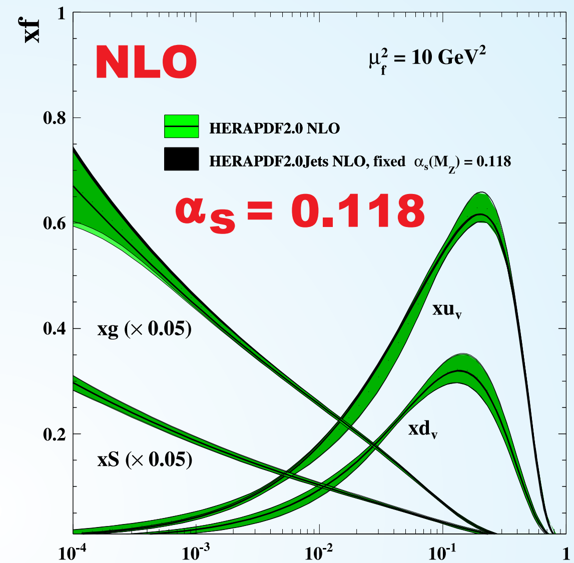




2.0 has a bit harder valence, especially at NLO and reduced gluon uncertainties at NNLO.

HERAPDF 2.0 Jets





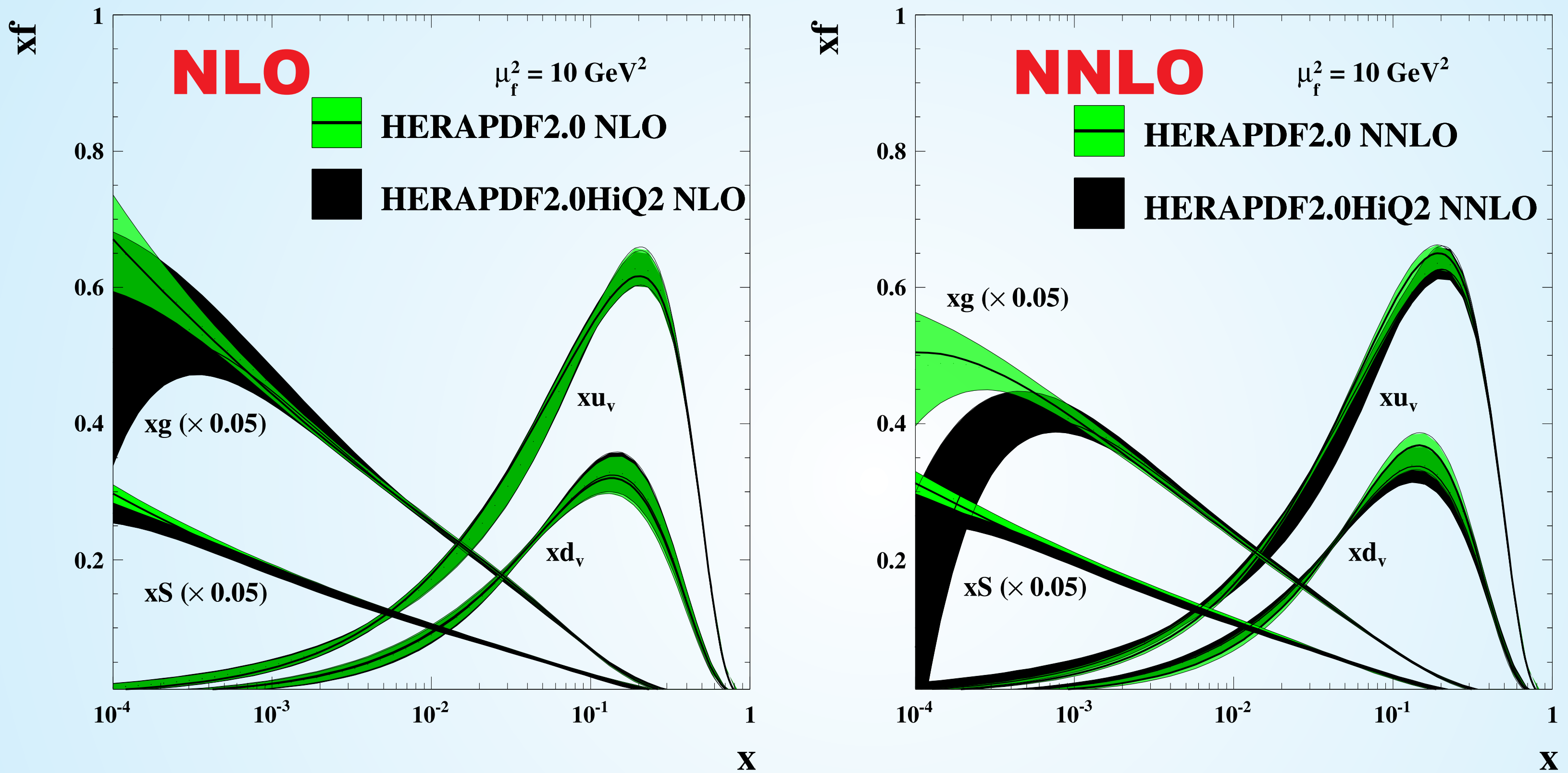
Jets are no problem to measure.

Jets is basically identical to NLO

α_s = 0.1183±0.0009(exp)
± 0.0005(model/param)
± 0.0012(hadronisation)
+ 0.0037 - 0.0031 (scale)

But, could some-body tell me what to do with the scale ?

HERAPDF 2.0 HiQ2

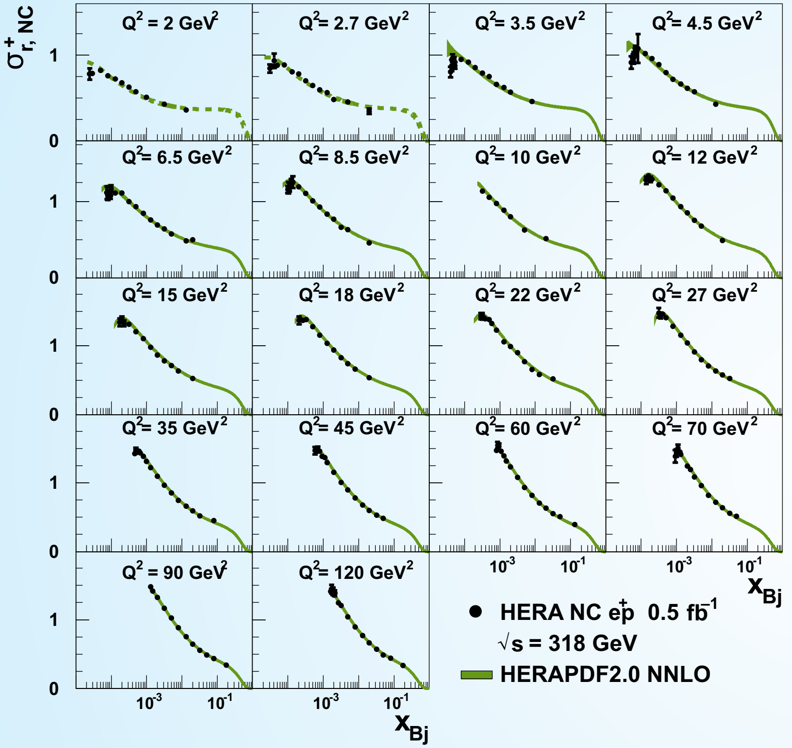


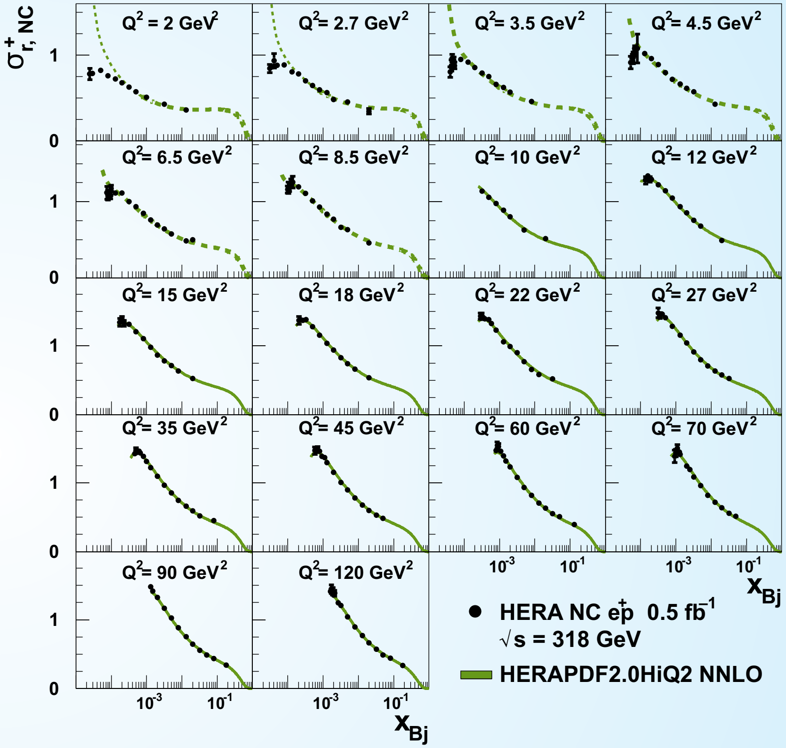
HERAPDF2.0 has a χ^2/dof of about 1.2.

Using only data with $Q^2 \geq 10 GeV^2$ reduces it to 1.15.

Heavy flavour schemes and FL make a difference, but ..

Comparison with data

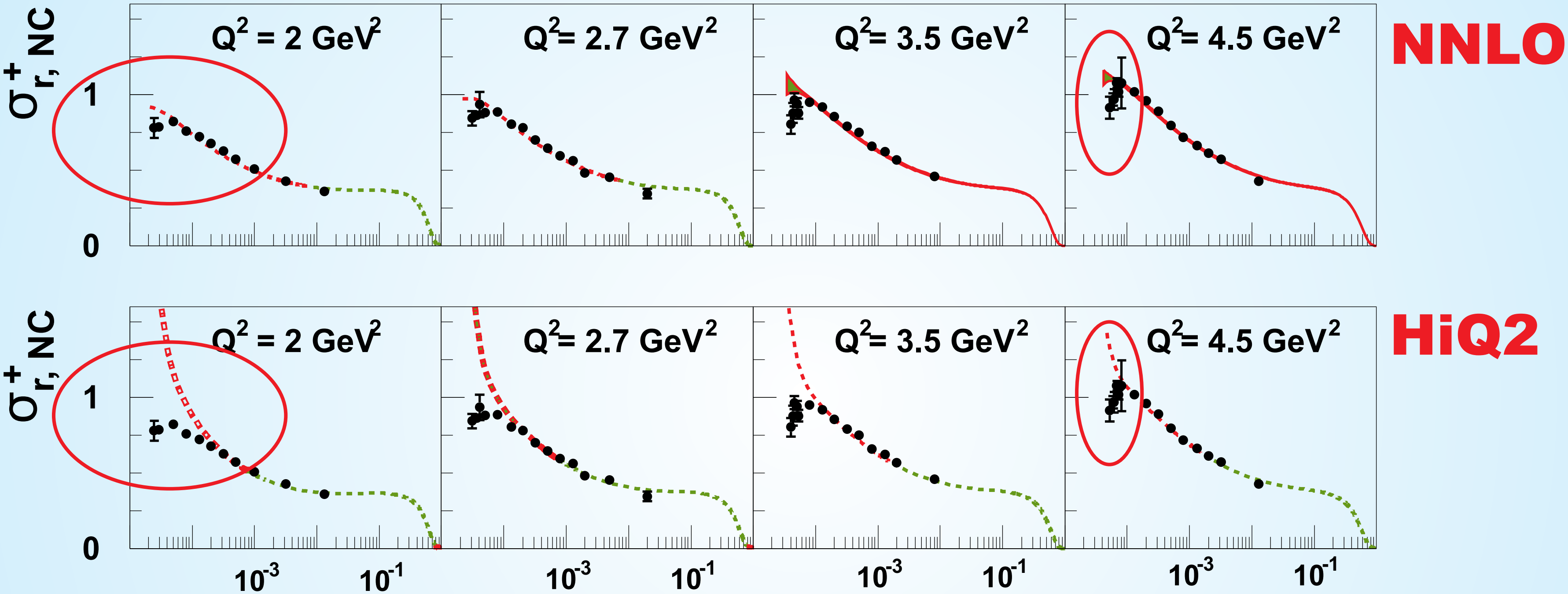




HERAPDF 2.0 NNLO | **HERAPDF 2.0 HiQ2**

For all these plots where everything fits, please see Eur. Phys. J C75 (2015) 580.

Comparison with data



The data show a turn-over, which NNLO does not really get. And HiQ2 evolves much too fast.

Low Q2 is also low x.

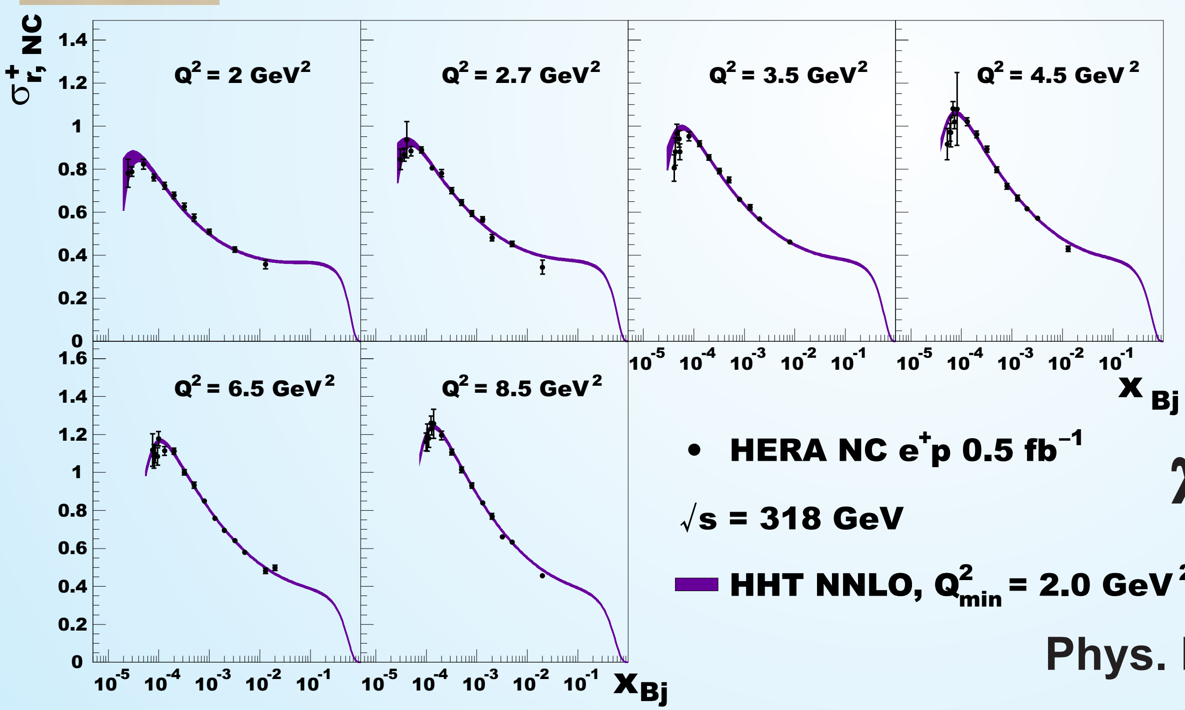
Fit Low Q^2

Why not work on low Q^2 data ?

Why not try some low Q^2 higher twist ?

$$F_L^{HT} = F_L^{DGLAP}\left(1 + A_L^{HT}/Q^2\right)$$

HHT [also RT a.o.]

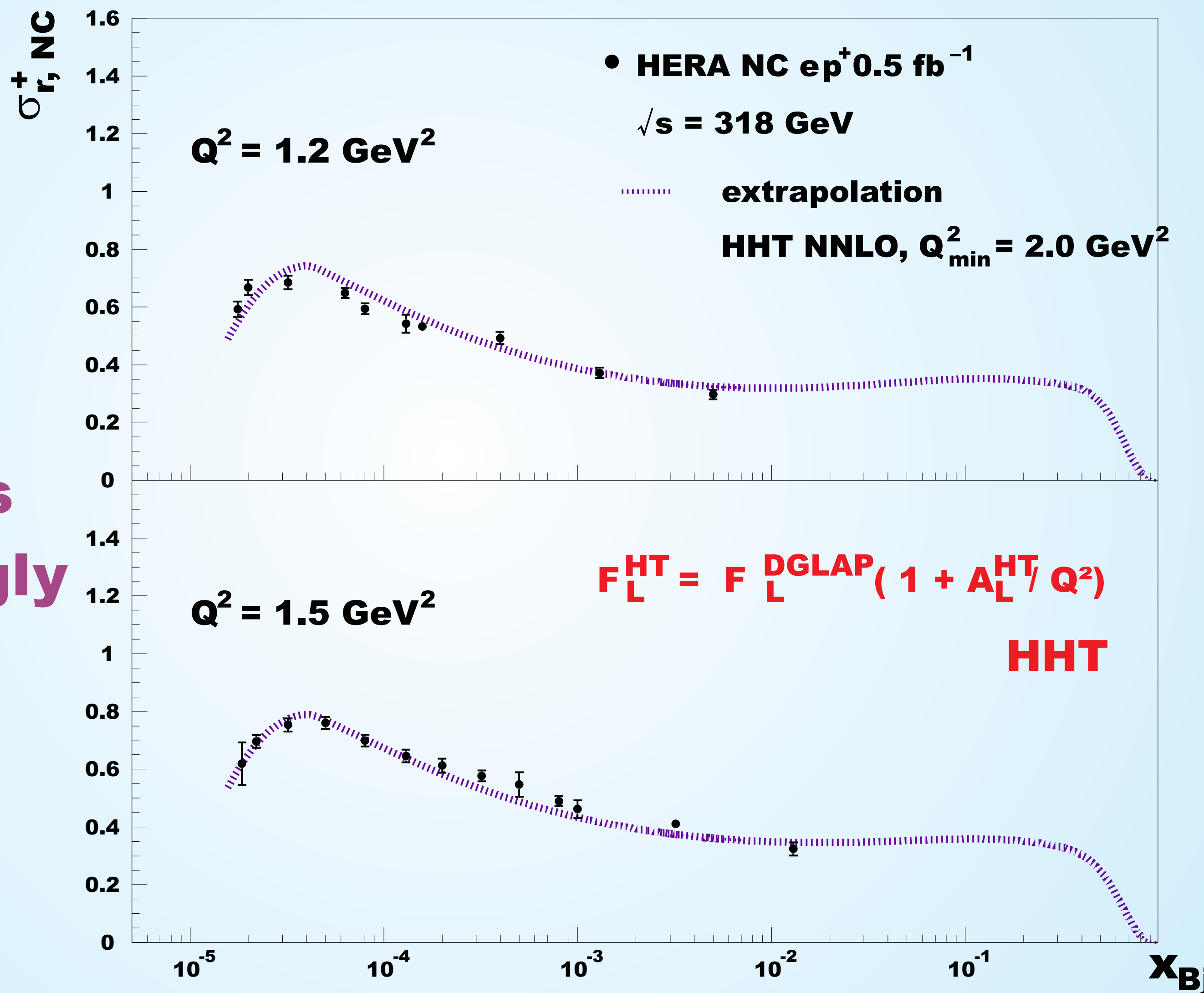


This is a possibility to fit the low Q^2 data.

χ^2: 1.22 → 1.18

Phys. Rev. D 94 (2016) 034032

Fit Low Q²

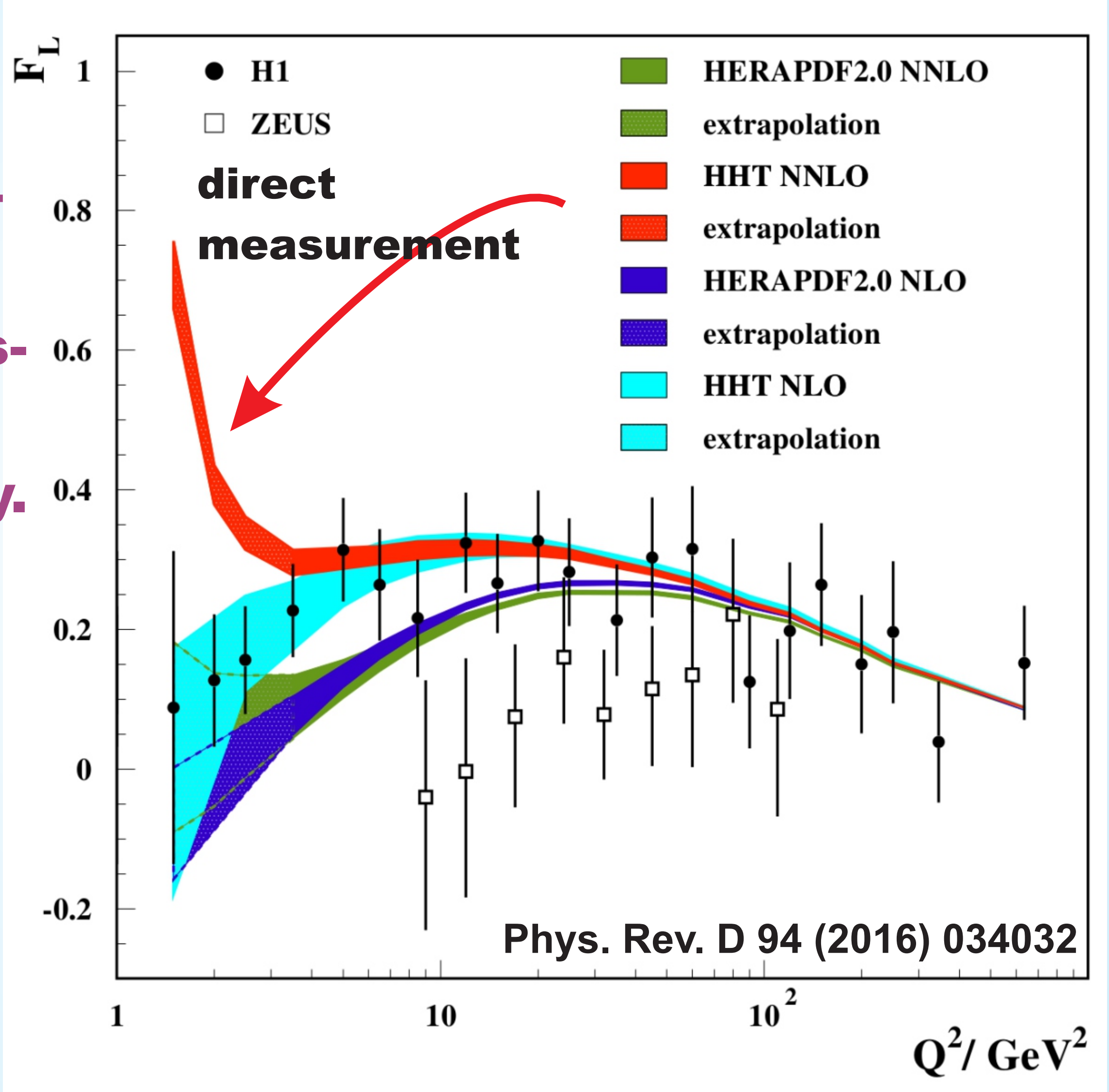


This works to amazingly low Q². But is this really a solution?

F_L

No, the resulting F_L is crazy.

Fitting cross-sections is not the whole story.



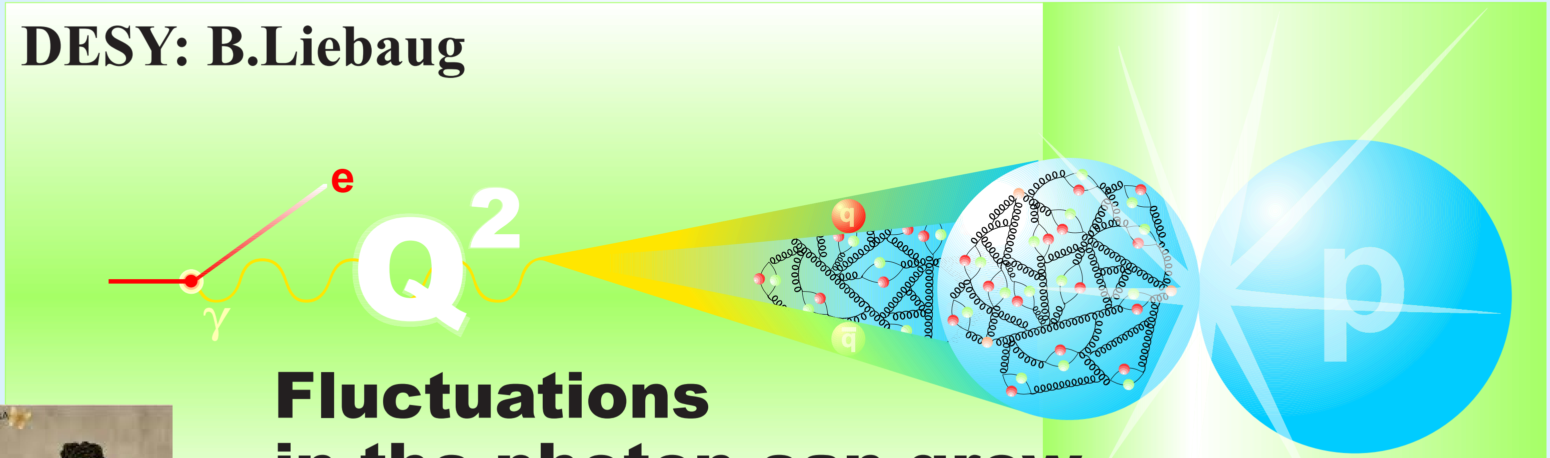
There is no HERA F_L

Grids were different – it was okay for the combination but the result lost some H1 info on correlations.

Low x Partons in the Proton ?

Heisenberg is strictly against it !

That x is a fraction of the proton momentum is only an interpretation.



Fluctuations
in the photon can grow.
For low Q^2 they live long and prosper.

There has to be more than DGLAP and pQCD.

Low Q²

F_2 was first

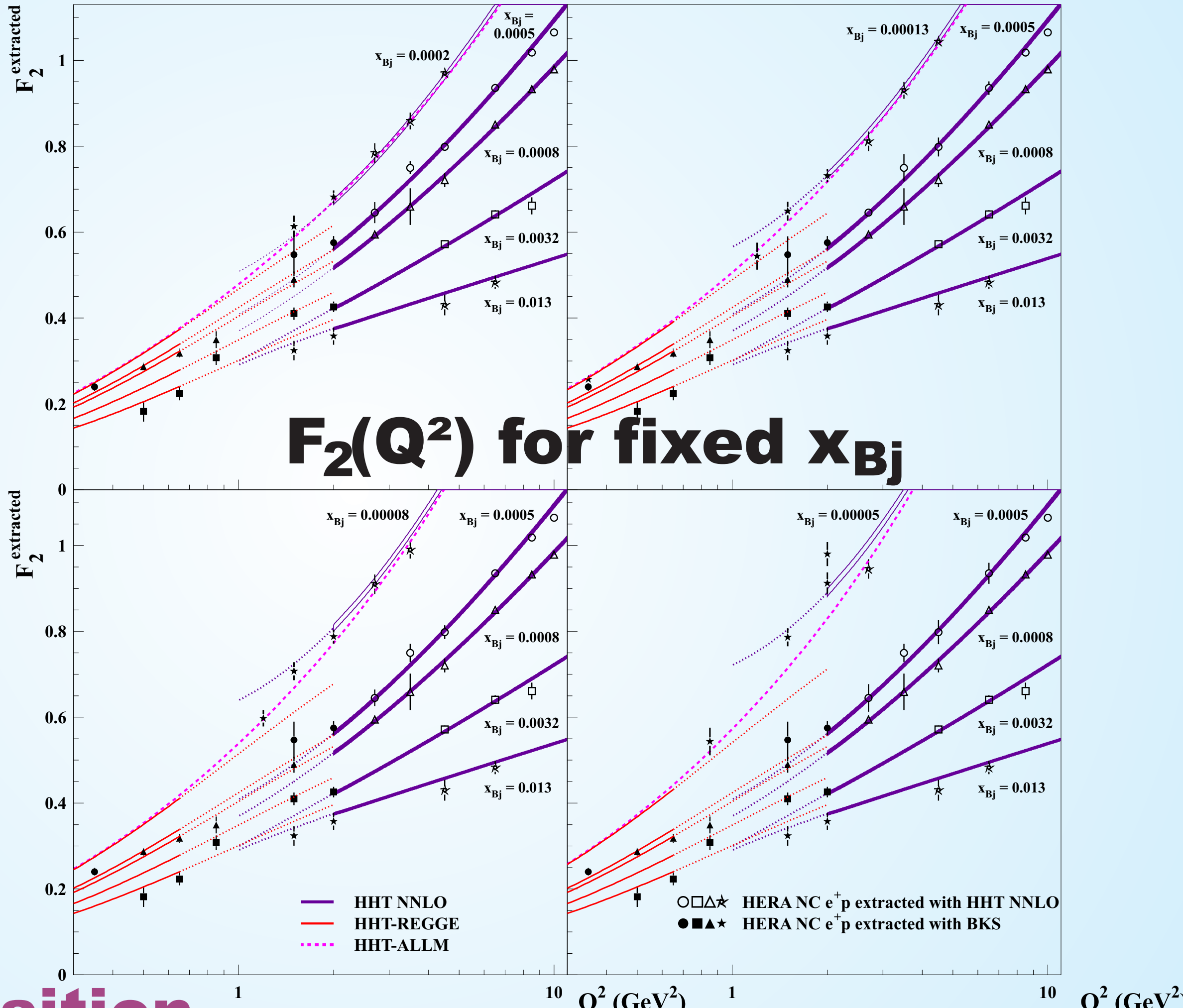
F_2 again

DGLAP

+ REGGE

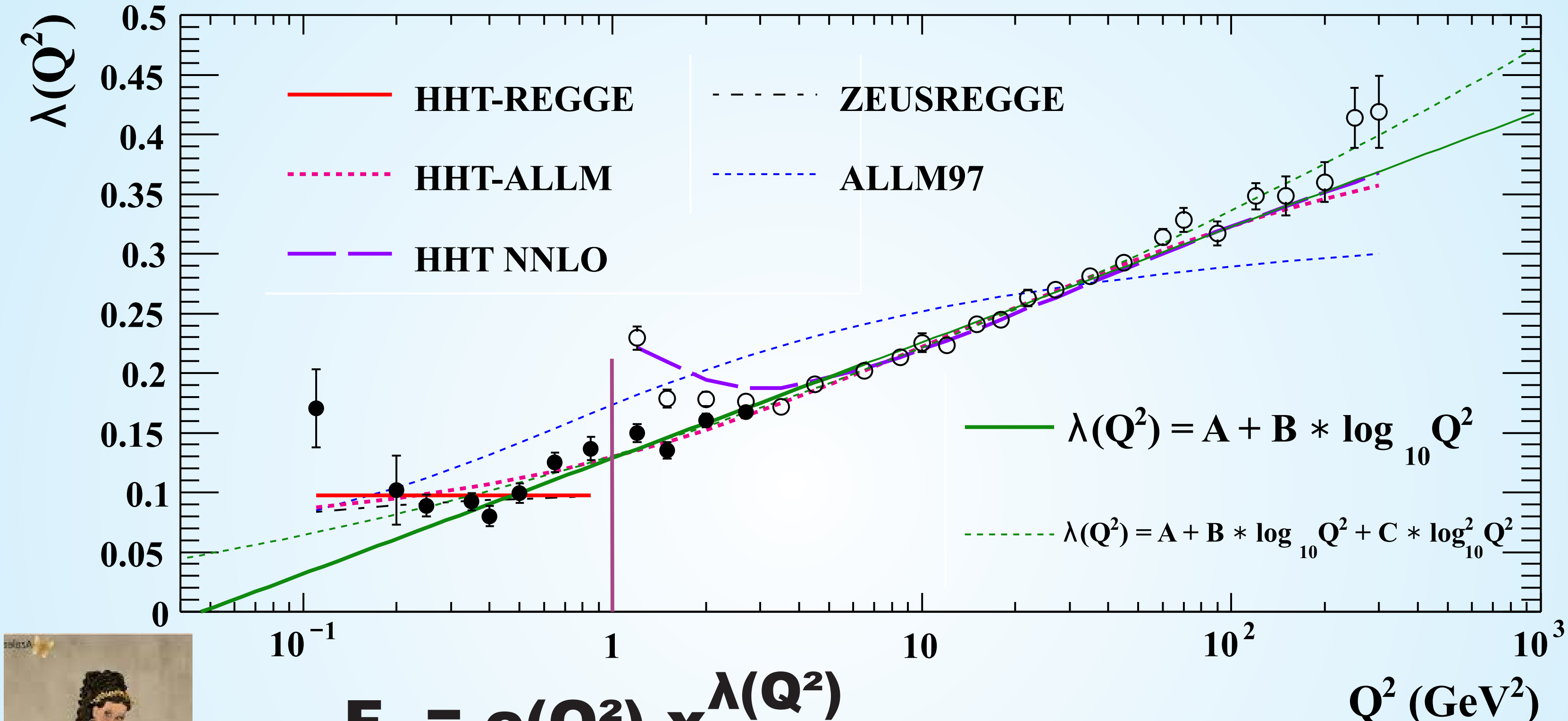
ALLM

The data know how to make a smooth transition.



Phys. Rev. D 96 (2017) 014001

Low Q²



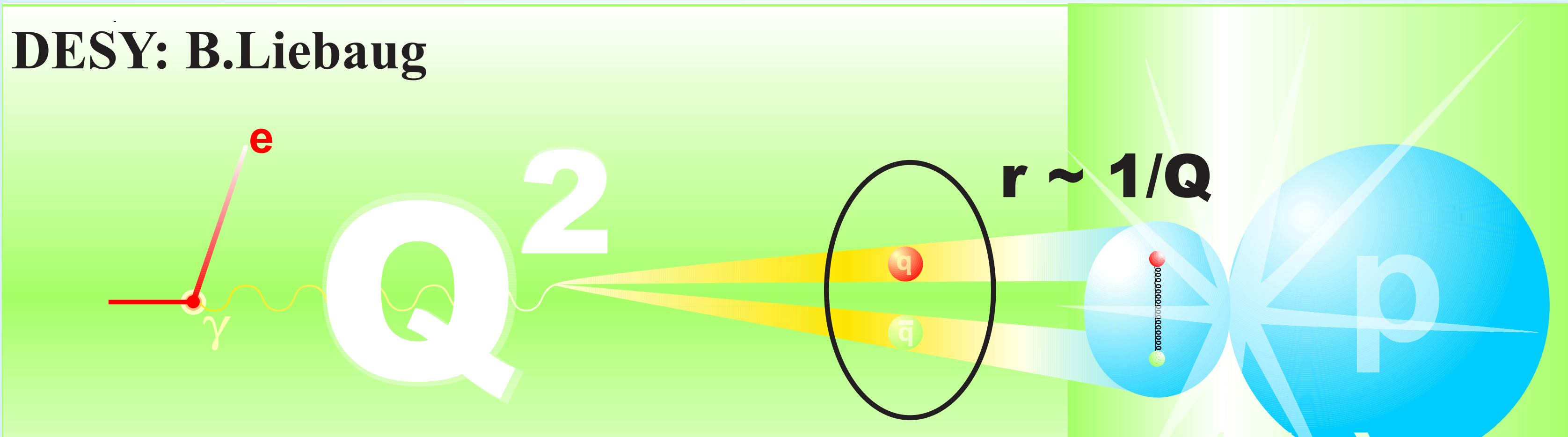
$$F_2 = c(Q^2)\, x_{Bj}^{\lambda(Q^2)}$$

If there is a transition, it is not at Q² = 1 GeV²

Phys. Rev. D 96 (2017) 014001

Color Dipole Model

Coherence length: l [fm] $\approx$ 0.1/x



For high Q^2 only a color dipole forms.
No time for more.

About two thirds of the excess in χ^2 come from high Q^2.

Let's see what theoreticians come up with.

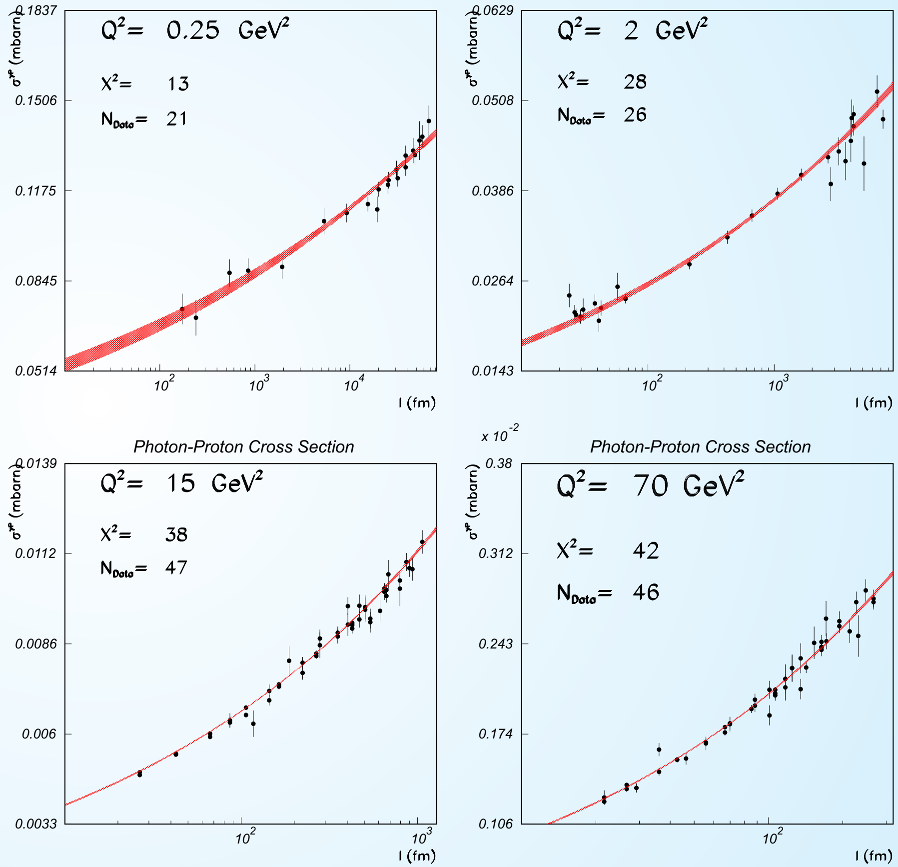
Data are simple

The dipole models is reasonably simple.

$$\sigma(l, Q^2) = \sigma_1(Q^2) \left(\frac{l}{1\ \mathrm{fm}}\right)^{\lambda_{eff}(Q^2)}$$

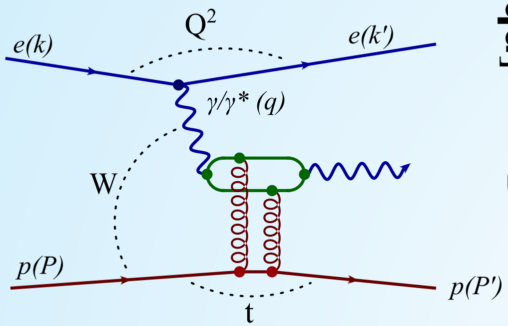
It works with a coherence length and does quite well.

photon proton cross secton

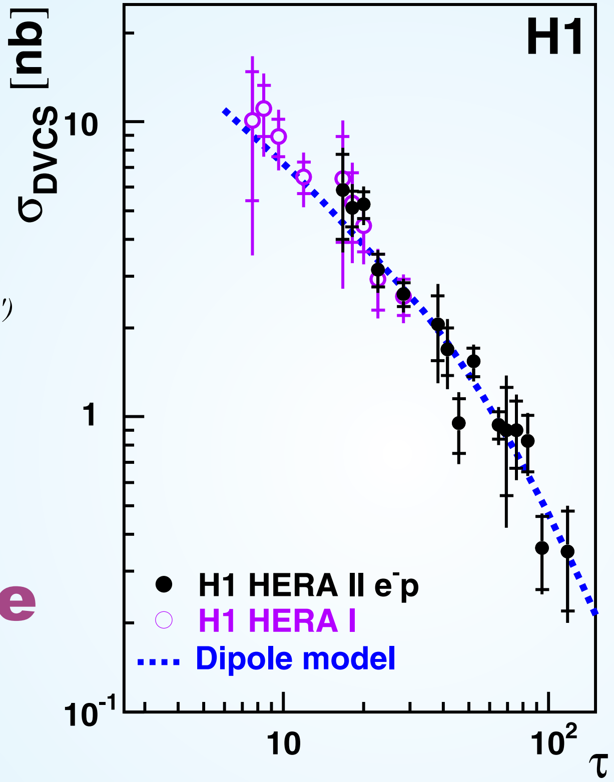


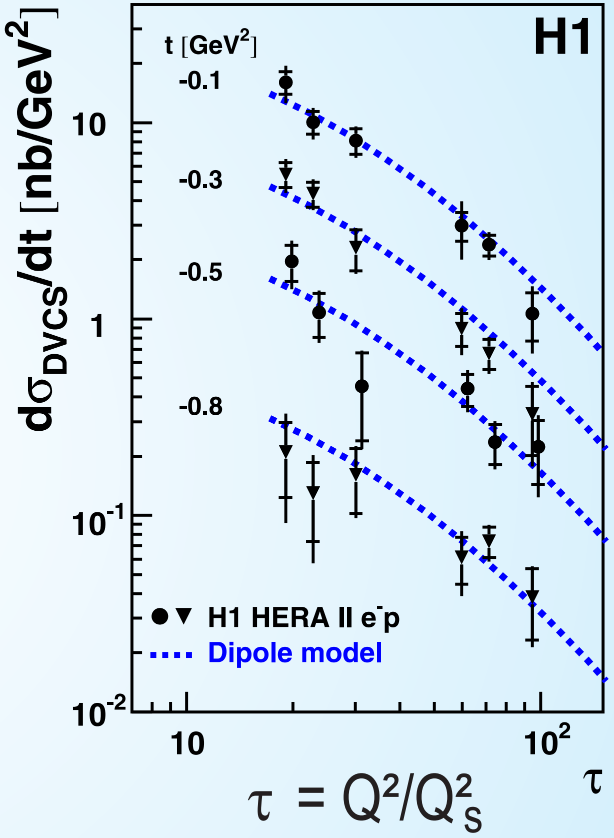
New Journal of physics, Vol 18, July 2016

Deeply Virtual Compton Scattering



Not all data are simple to get.

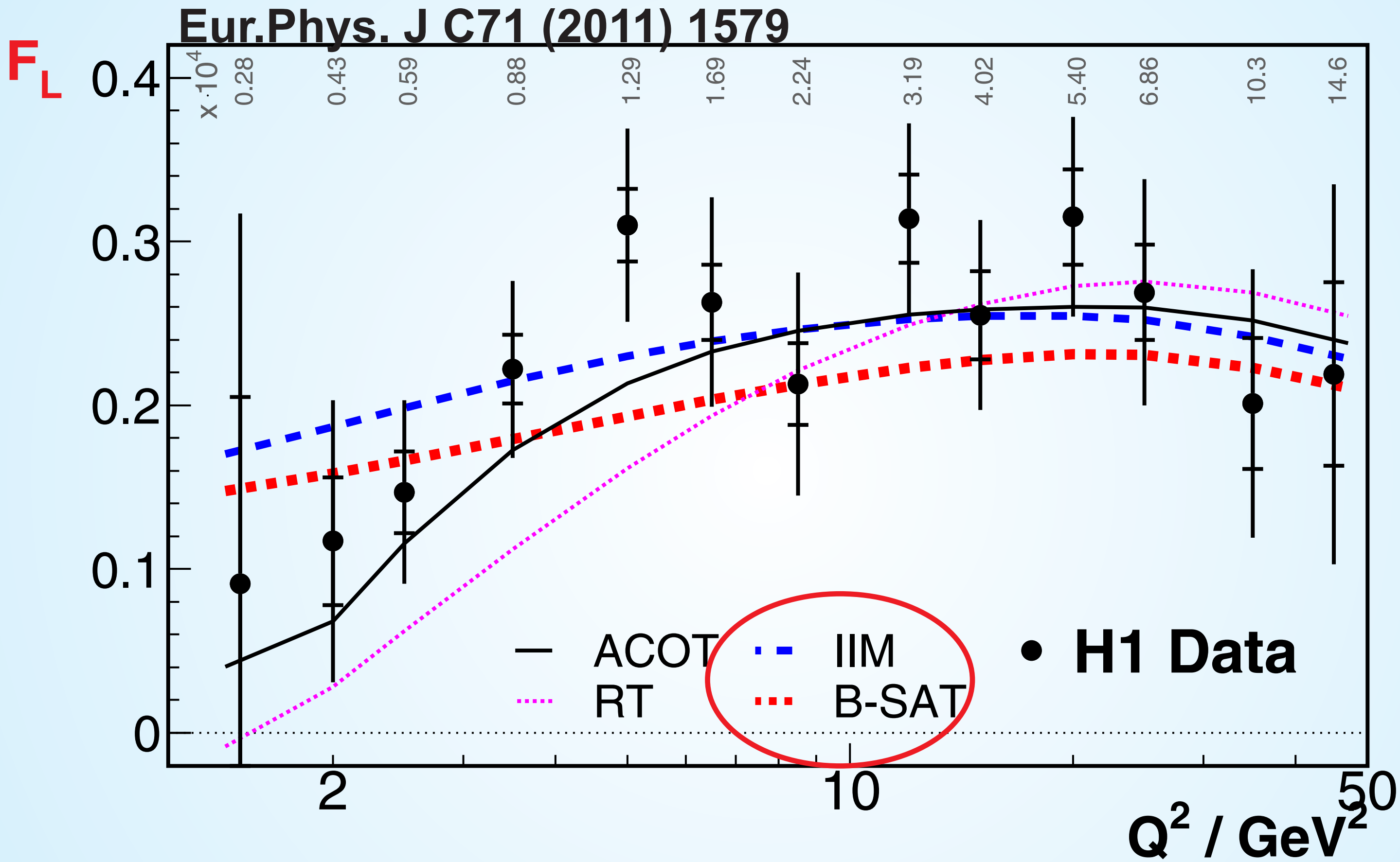




The dipole model does well.

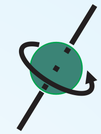
Phys.Lett. B 659 (2007) 796

Longitudinal Structure Function



Color dipole models can describe F_L.

Electroweek Studies

It would be nice to have a combination of cross sections for  pol = x%

Uncertainties on polarisation were treated differently.

Radiative corrections where not done the same way.

data will stay apart.

/ HH have papers out, will come soon.

If common papers are wanted, you need to start coordination early.

Radiative Corrections

ZEUS and H1 agreed early on to correct all cross sections to “Born level” by applying LO radiative correction on the electron.

The MC changed over time and the interpretation of LO was not always the same.

→ Impossible to undo and switch to NLO
Extra uncertainties for studies with ZEUS + H1 data.

Publish the corrections you made,
so that they can be undone in the future.
Best, you publish event numbers.

I am dead serious !

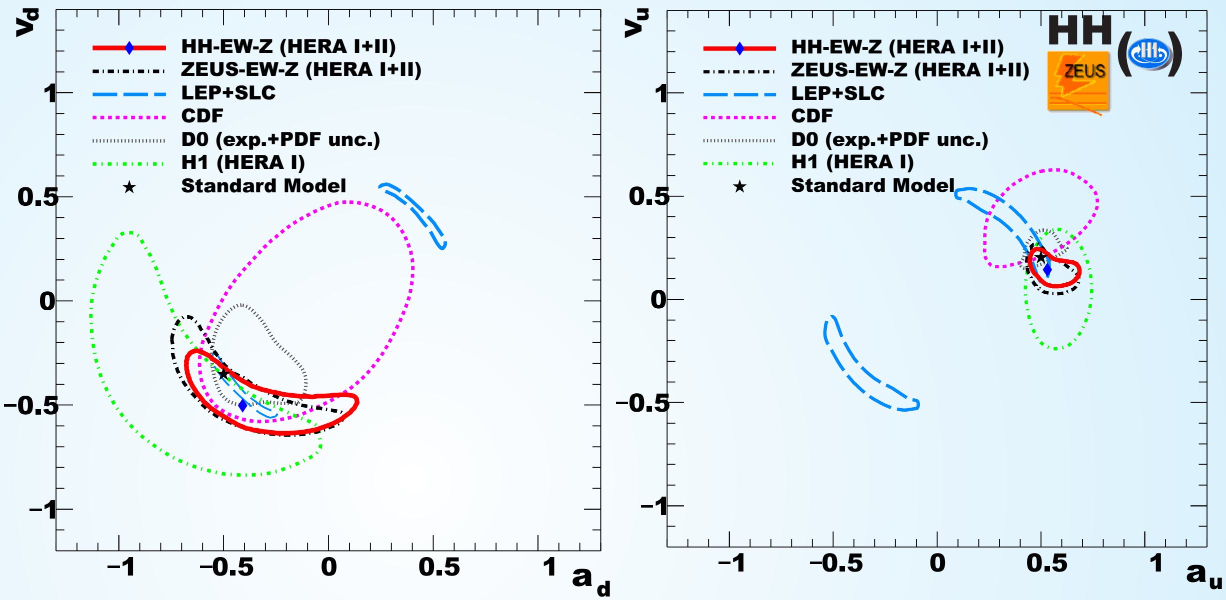
Electroweek Studies

pol = x%

Fit PDFs and electroweek parameters

NLO in QCD

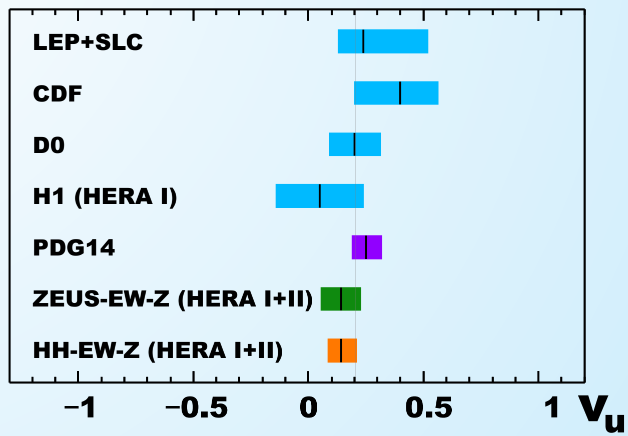
“LO” in EW



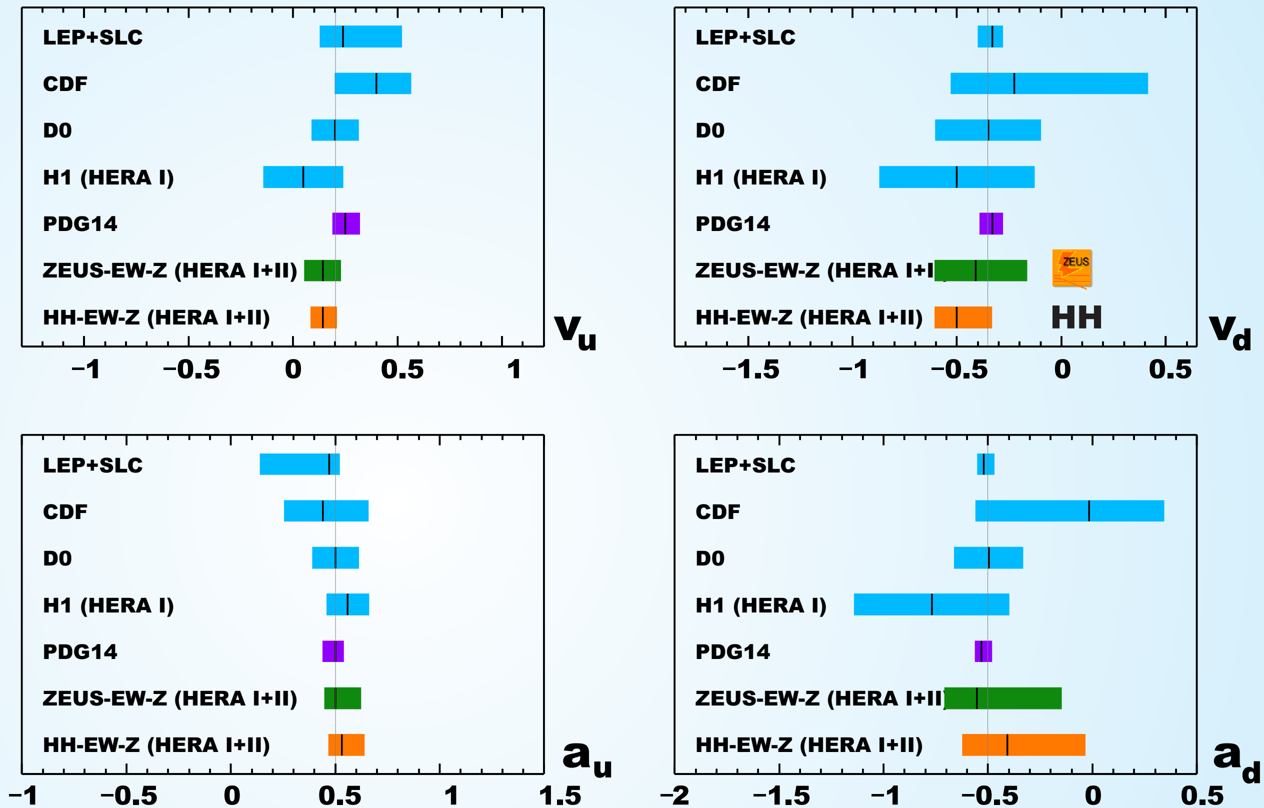
Sometimes, I surprise myself. This is actually the best on v_u around.

Phys.Rev. D94 (2016) 052007 HH

Phys.Rev. D93 (2016) 092002



Electroweek Studies



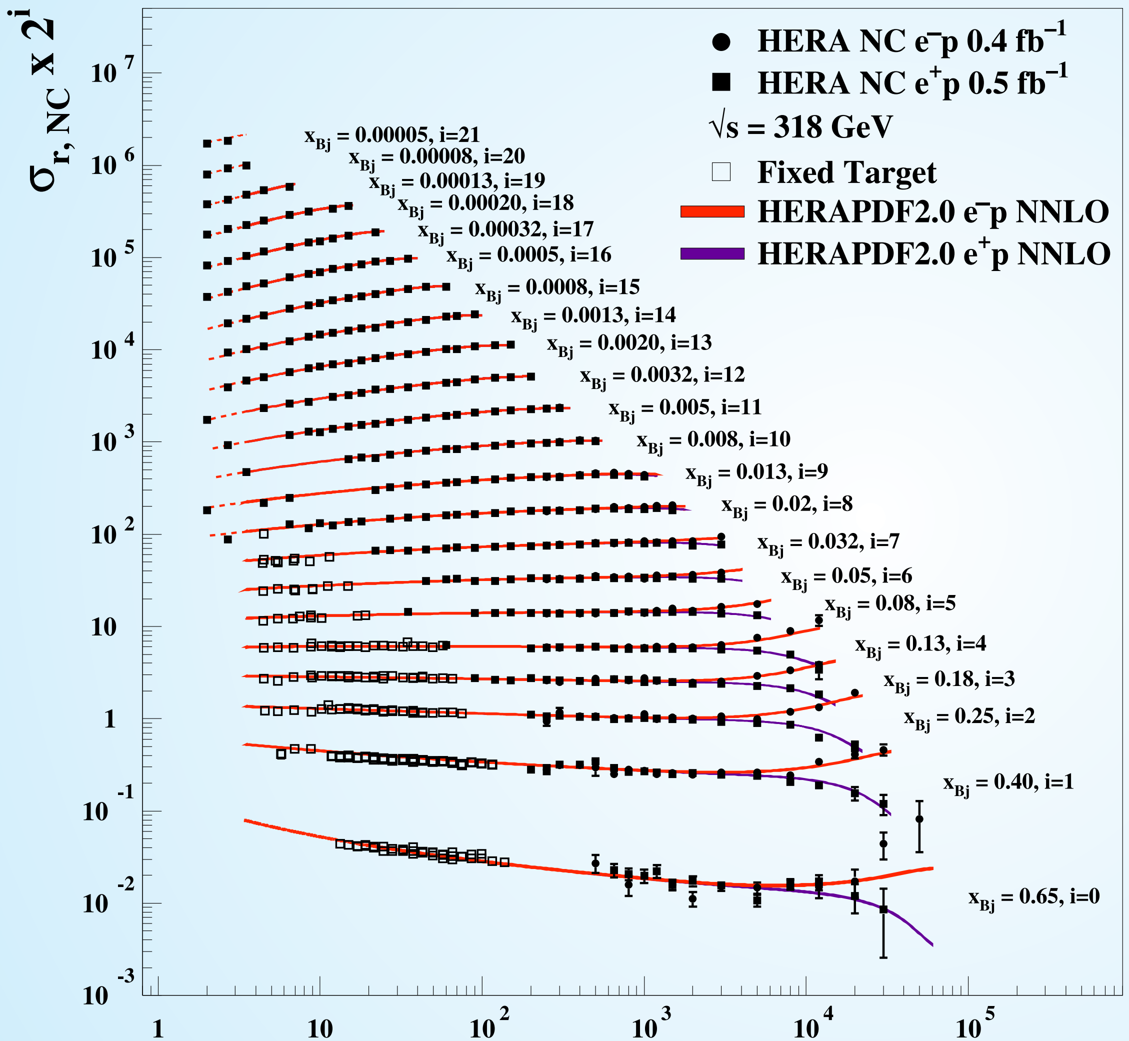
And at the same time they fitted

$$\sin^2\theta_W = 0.2252 \pm 0.0011 \,{}^{+0.0003}_{-0.0001}\,{}^{+0.0007}_{-0.0001}$$

exp./fit model param.

M_W was done, but improvements are expected.

Legacy Plots



Eur. Phys. J C 75 (2015) 580

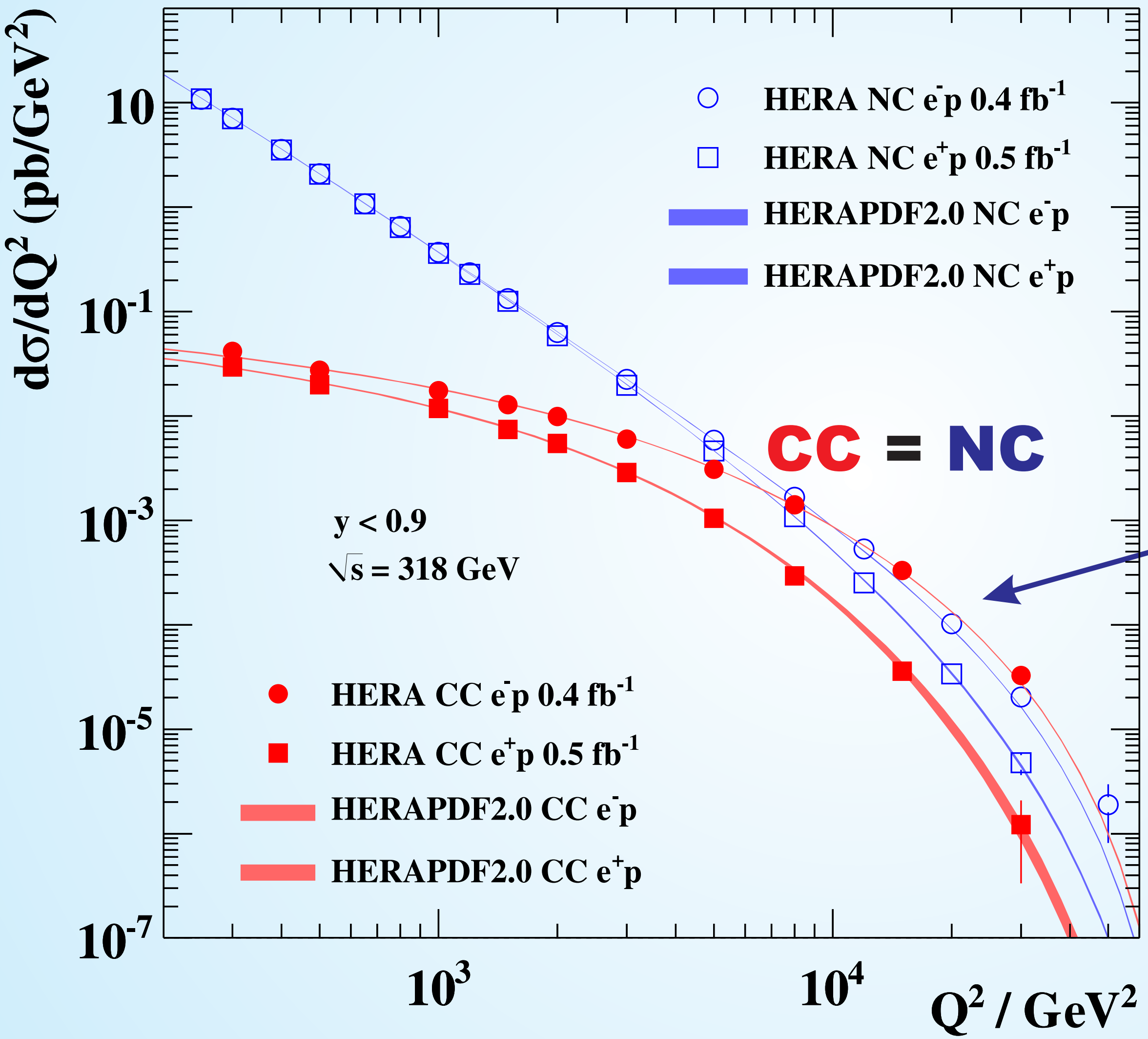
HERA electron and positron and fixed target data

nice, isn't it

Q^2: 2 – 50000 GeV^2

x: 0.00005 – 0.65

Legacy Plots



CC = NC

high Q²

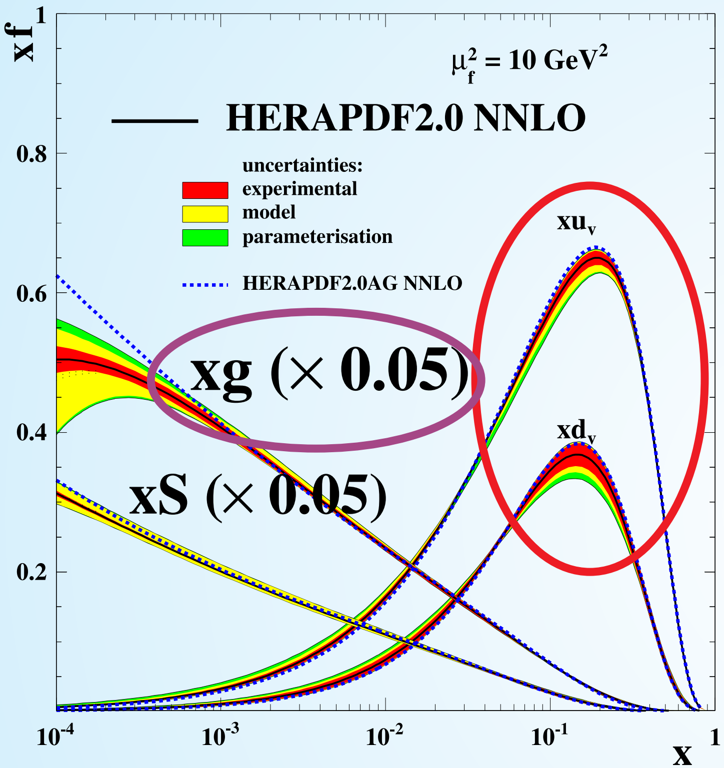
NC

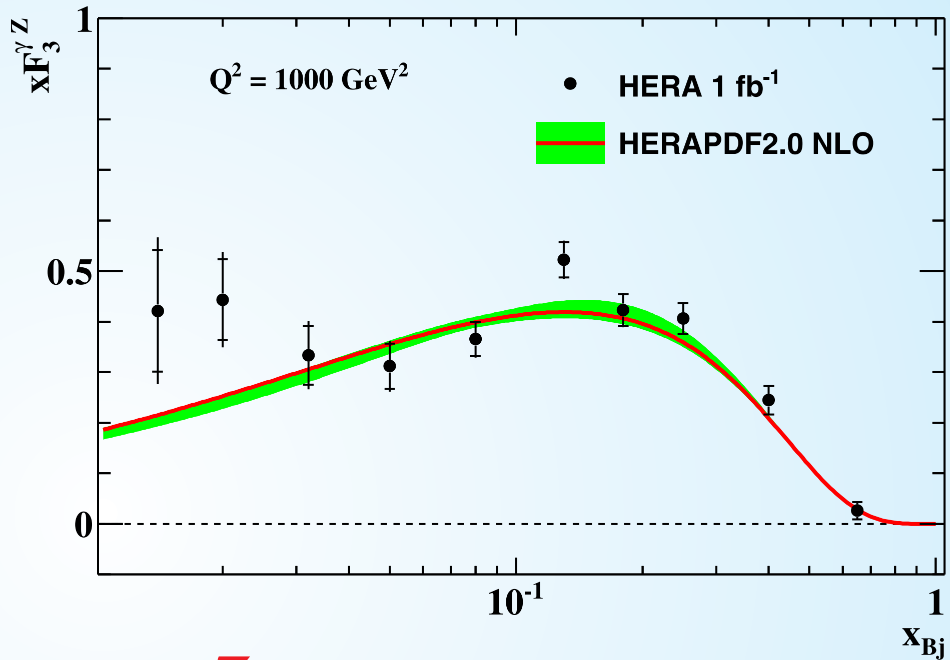
CC

xF_3

difference between positron and electron data

Valence Quarks





$$xF_3^{\gamma Z} \approx \frac{x}{3} \left[\, 2u_V + d_V \, \right]$$

Have these gluons, have PDFs anything to do with the proton or with what happens in the interaction?

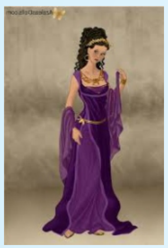
Back to the proton →

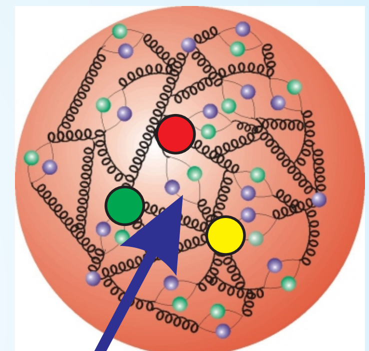
Proton Size and Dynamics

rms charge radius

electron: 0.8786 ± 0.0069 fm

muon: 0.84184 ± 0.00067 fm

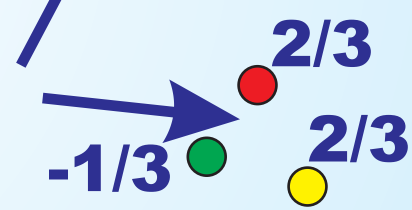




rms glue/sea radius?

DVCS : 0.65 ± 0.02 fm

What a misleading picture I promoted



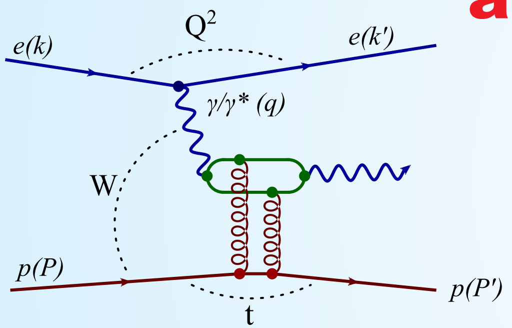
dipole moment: < 0.54 10^{-23} ecm

Can we measure a dynamic system while averaging over time? Heisenberg again....

Deeply Virtual Compton Scattering

Generalised parton distribution functions are used for two gluon interactions.

Interpretation in longitudinal momentum space and transverse position space



$d\sigma/dt \sim \exp(-b|t|)$

$b = 5.45 \pm 0.19 \pm 0.34\ /\mathrm{GeV}^2$

average impact parameter

0.65 ± 0.02 fm $x=0.0012$

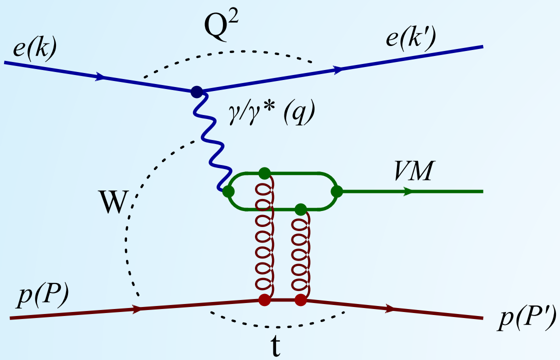
transverse expansion of partons

-- in the proton?

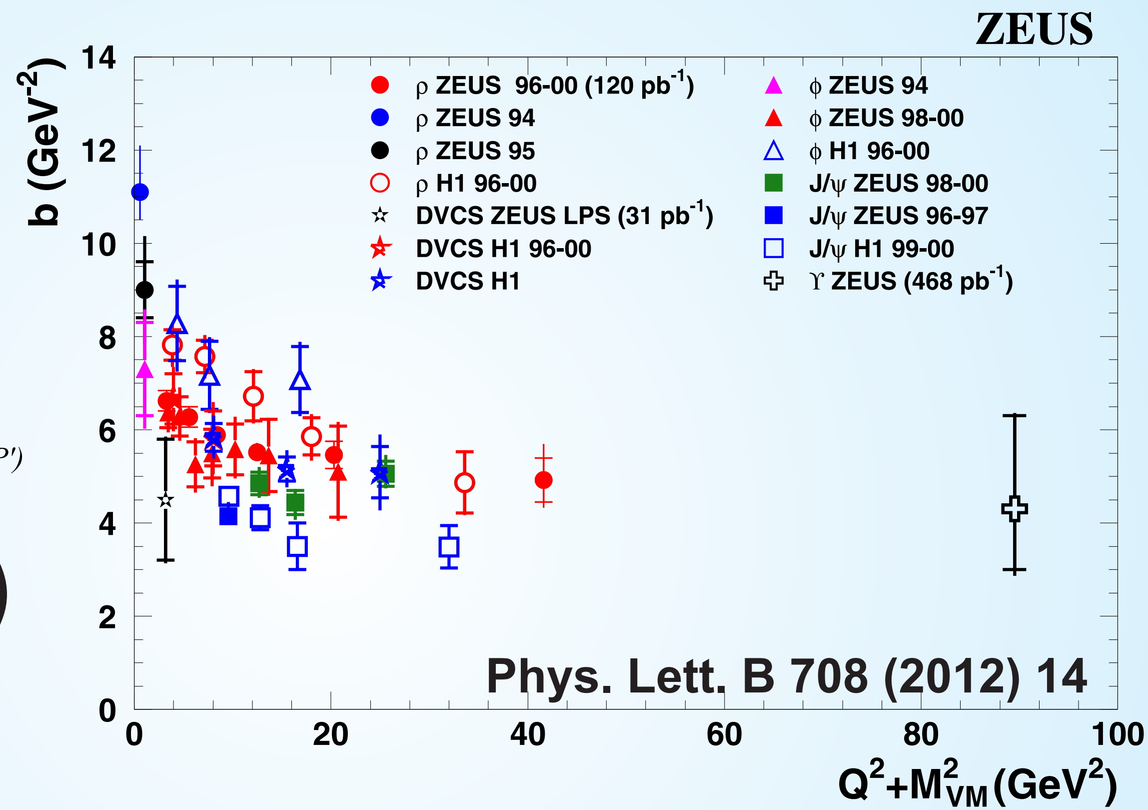
Eur.Phys. J C71 (2011) 1579

t-Slopes for Vector Meson Production

data



$$d\sigma/dt \sim \exp(-b|t|)$$



Should be analysed with respect to impact parameter / proton size.

What will you see for ions? The π cloud?

Proton Shape

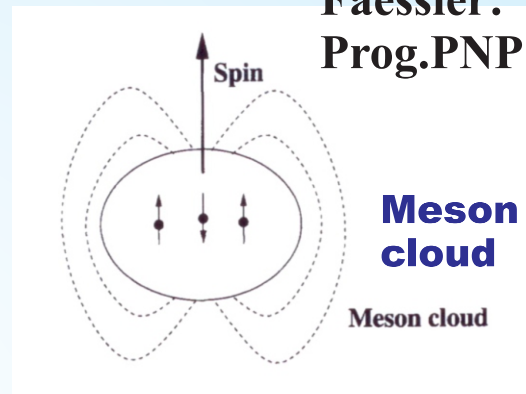
magnetic moment

$\mu_{p}/\mu_{N} = 2.792847356 \pm 0.000000023$

$p \rightarrow \Delta$ excitations

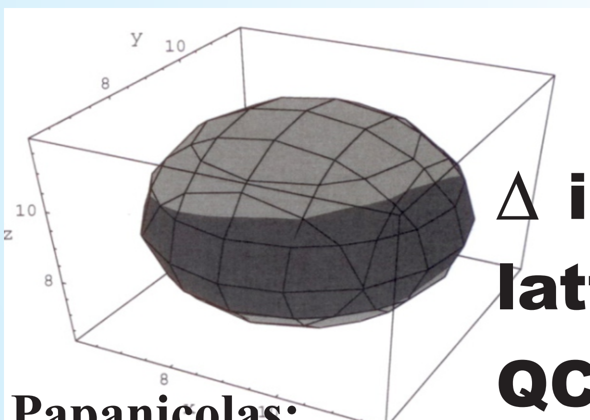
[also used for GZK cutoff]

Faessler:
Prog.PNP 44(2000)



EMC effect

There has to be some cloud, otherwise protons cannot bind.



Δ in lattice QCD

Papanicolas:
EPJ A 18(2003)

Did I see the proton or some strong field created in the interaction?

Remember HERA

for her cross sections

and use them to test your ideas !

for her PDFs

and use them with care to predict your cross sections !

for her enormous range and flexibility

and when you publish your data, think about the long term possibilities and publish all numbers !

for the problems she had to overcome

and try to avoid them !

and for her data which were preserved !

If you have an idea, join us.